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MODERN WORKSHOP TECHNOLOGY

IN THREE PARTS

PART II

MACHINE TOOLS & MANUFACTURING PROCESSES

SECOND EDITION

CLEAVER-HUME PRESS LTD
LONDON

CLEAVER-HUME PRESS LIMITED
31 *Wright's Lane, London W* 8

SECOND EDITION
© CLEAVER-HUME PRESS LTD 1960

First published 1950
Second edition, revised and rearranged 1960

Demy 8*vo, xiii* + 652 *pages*

281 *line and* 139 *half-tone*
illustrations 22 *tables*

Printed in Great Britain by
WESTERN PRINTING SERVICES LTD, BRISTOL

PREFACE

IN the preparation of the second edition of Volume II we have endeavoured to make a somewhat more systematic approach to the subjects covered, and to bring each section up to date within the scope of the book. This has involved not only the introduction of new topics, but the rewriting of several chapters, sometimes from a different angle and by fresh contributors. The result has been a notable increase in the length of the volume, but it is hoped that there is a more than proportionate increase in its value.

It has seemed essential in the first section to break with the old traditions according to which each type of machine tool was considered as a separate creation, and, instead, to see them as members of a single family having many features in common and with differences dictated more by convenience than by principle. There are many books which show how a lathe can turn, and which indicate the very wide range of work which, if necessary, it can be made to cover, but there is very little information available in a convenient form which shows how the work can be done economically by modern standards, perhaps with automatic operation and control, and using materials which were undreamed of a generation ago.

In certain fields such as that of the understanding of the processes involved in the actual cutting of metals– much new knowledge is being gained, but at present the intricacies of the new theories tend to explain known facts rather than point the way to new practices. In this section the trends of recent researches have largely been omitted to avoid complicating general problems. On the other hand it has been felt necessary to deal in detail with some of the intricate problems of "Surface Finish" in order to help the reader to weave his way with fair safety through the maze of technical and academic literature which appears at times to bedevil his progress, the latter type sometimes seemingly justifying the use of inverted commas and a capital "A".

The recently developed techniques of ultrasonic and electrical machining have been added, and much care has been given to the coordination of all these contributions, so as to form a coherent picture of the latest views and practice.

It is hoped the book will provide answers to many of the machining problems which arise in small and medium-sized workshops and that a third volume will add information concerning the principles involved in the selection and running of more complex plant for large-scale production.

H. Wright Baker

Manchester,
May 1960

CONTENTS

PREFACE v
THE EDITOR

I METAL CUTTING MACHINE TOOLS 1
F. KOENIGSBERGER D.SC. DIPL.-ING. M.I.MECH.E. M.I.PROD.E. MEM.A.S.M.E. *Reader in Machine Tools and Production Processes, University of Manchester*

II THE THEORY OF CUTTING TOOLS 51
A. W. J. CHISHOLM B.SC.(ENG.) A.M.I.MECH.E. A.M.I.PROD.E. *Head of Department of Mechanical Engineering, Royal Technical College, Salford*

III TURNING 92
F. KOENIGSBERGER

IV MILLING 116
F. KOENIGSBERGER

V DRILLS AND DRILLING MACHINES 144
F. M. BIRCH A.M.I.PROD.E. *Jones and Shipman Ltd, Leicester*

VI BROACHING 163
E. PERCY EDWARDS M.I.PROD.E. *Consultant*

VII SHAPING, PLANING AND SLOTTING 173
J. V. BRITTAIN B.SC.(ENG.) A.M.I.E.E.

VIII Part 1: PRECISION GRINDING 186
R. J. McL. WHIBLEY A.M.I.MECH.E. *The Churchill Machine Tool Co. Ltd, Manchester*

Part 2: ULTRASONIC MACHINING 217
E. A. NEPPIRAS B.SC. A.R.C.S. *Mullard Research Laboratories*

IX SCREW THREAD PRODUCTION 229
H. H. PEACE *International Twist Drill Co. Ltd, Sheffield*

X GEARS AND GEAR CUTTING 246
H. J. WATSON B.SC. A.M.I.MECH.E. *Head of Research and Development, David Brown Industries Ltd (Park Works), Huddersfield*

XI ELECTRIC MACHINING OF METALS 290
M. M. BARASH B.SC. DIPL.-ING. PH.D. *Lecturer in Mechanical Engineering, University of Manchester*

XII Part 1: SHEET METAL DRAWING 316
H. W. SWIFT M.A. D.SC. (ENG.) M.I.MECH.E. *Emeritus Professor of Engineering in the University of Sheffield*

Part 2: LOAD CONDITIONS OF BLANKING AND DEEP DRAWING OPERATIONS 33
F. KOENIGSBERGER

XIII PRESSWORK 342
J. A. SIMMS A.M.I.MECH.E. M.S.A.E. *Pressed Steel Company Ltd. (Linwood Factory), Paisley, Scotland*

XIV MEASUREMENT STANDARDS AND EQUIPMENT 361
L. W. NICKOLS B.SC. M.I.MECH.E. M.I.PROD.E. *Principal Scientific Officer, Standards Division, National Physical Laboratory*

XV INSPECTION I 378
L. W. NICKOLS

XVI INSPECTION II 389
L. W. NICKOLS

XVII Part 1: THE MEASUREMENT OF SURFACE TEXTURE 413
R. E. REASON A.R.C.S. *Taylor, Taylor and Hobson, Leicester*

Part 2: THE PREPARATION OF FINE SURFACES 475
D. B. EBSWORTH M.I.PROD.E. M.I.F.I. *Bristol Siddeley Engines Ltd.*

XVIII JIGS AND FIXTURES 486
H. FOWLER *Chief Planning Engineer, Leyland Motors Ltd, Leyland, Lancashire*

XIX FRICTION, LUBRICANTS AND CUTTING FLUIDS 513
I. S. MORTON B.SC. A.M.I.MECH.E. A.M.I.PROD.E. and
A. L. H. PERRY B.SC.TECH. F.I.M. *Oil Products Department, Shell International Petroleum Company Ltd.*

XX HEAT TREATMENT APPLIANCES 554
H. J. BRAY B.SC.(ENG.) PH.D. F.I.M. *Senior Lecturer in Metallurgy, University of Manchester*

XXI ELEMENTS OF PRODUCTION ENGINEERING 574
J. SAXBY *Production Engineer, Mirrlees, Bickerton and Day Ltd, Stockport, Cheshire*

XXII PRINCIPLES OF STANDARDIZATION 591
F. KOENIGSBERGER

XXIII SAFETY DEVICES 597
H. A. HEPBURN C.B.E. B.SC.(ENG.) M.I.MECH.E.
Industrial Safety Consultant, sometime H.M. Inspector of Factories

XXIV HUMAN RELATIONS IN THE WORKSHOP 613
A. ROBERTS M.COM. PH.D. F.B.I.M. *Reader in Industrial Administration, University of Manchester*

BIBLIOGRAPHIES & REFERENCES 627

METRIC CONVERSION FACTORS 63

INDEX

CHAPTER I

METAL CUTTING MACHINE TOOLS
PRINCIPLES OF DESIGN AND USE

By F. KOENIGSBERGER, D.Sc., Dipl. Ing., M.I.Mech.E., M.I.Prod.E., Mem. A.S.M.E.
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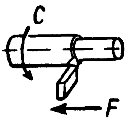
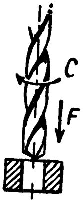
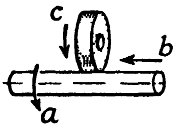
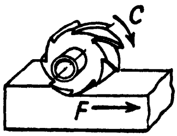
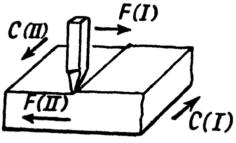
University of Manchester

Spindle and Feed Drives. The action of a metal cutting tool is based on the relative movement between the tool edge and the material to be cut. If the cutting action is intermittent, as in the planing machine and the shaper, then, as soon as the cut has been made, fresh material must be fed in front of the cutting edge if the operation is to be repeated. If, however, the operation is continuous, as in the lathe, drilling machine, cylindrical grinder or milling machine, both cutting and feeding motions may be simultaneous and continuous. Machine tool mechanisms have to provide both the cutting and the feeding movements, each of which may be allotted either to the tool or to the work piece (Table 1.1).

Spindle Drives. The relative velocity between the tool edge and the material to be cut is called the cutting velocity v, and its optimum value has to be chosen in accordance with the properties of the tool and those of the workpiece material and shape (*see* page 96). Universal machine tools must be suitable for machining many materials and various shapes of workpieces, and a wide range of cutting velocities, varying between a maximum v_{max} and a minimum v_{min}, must therefore be available. If the relative velocity v of the cutting movement is produced by rotation of either the workpiece or of the tool, the required number of revolutions per minute n of the rotating part (the spindle speed) is determined by its diameter, d in Fig. 1.1. In the equation $v = \pi dn$, d is the cutting diameter of the rotating tool or the diameter of the surface that is to be cut by the machining operation in question. On a universal machine tool, d may vary between possible maximum and minimum depending on the capacity of the machine.

TABLE 1.1

Type of Operation	*Cutting Movement 'C'*	*Feed Movement 'F'*
Turning  	Workpiece	Tool
Drilling  	Tool	Tool
Cylindrical Grinding  	Tool	Workpiece (*a*) and Tool (*b*) or Workpiece (*a* & *b*)
Milling  	Tool	Workpiece
Planing (I) Shaping (II)  	Workpiece (I) Tool (II)	Tool (I) Workpiece (II)

The optimum spindle speed n depends, therefore upon diameter d and recommended cutting velocity v,

$$\text{i.e. } n = \frac{v}{\pi d}.$$

and in order to provide the beforementioned ranges for v and d, spindle speeds should be available which cover a range between

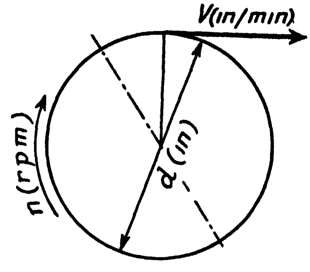


Fig. 1.1

$$n_{\max} = \frac{v_{\max}}{\pi d_{\min}} \quad \text{and } n_{\min} = \frac{v_{\min}}{\pi d_{\max}}$$

It is usually not practicable to provide an infinitely variable range of spindle speeds, and thus the exact optimum value of the cutting velocity cannot always be obtained. However, it is possible to establish certain limits for cutting velocities used in connection with the tool and workpiece materials in question. The top limit $v_{\max}$ would be the highest permissible velocity with which a required minimum tool life can be obtained, and the bottom limit $v_{\min}$ is the lowest economically justifiable velocity. If the cutting velocity is plotted as a function of the diameter of the rotating part a straight line is obtained for each spindle speed n (Fig. 1.2). If the spindle rotates at n_1 r.p.m., the diameter must not be larger than d_1 and not smaller than d_2, in order to keep between the limits $v_{\max}$ and $v_{\min}$. For diameters smaller than d_2 a higher spindle speed n_2 is required, and this is suitably chosen in such a manner as to provide again the maximum permissible cutting velocity $v_{\max}$ for d_2, covering an economically machinable range of diameters down to diameter d_3. Similarly n_3, n_4, etc. can be chosen. In general terms

$$\begin{aligned} v_{\max} &= \pi d_n \,.\, n_n \\ &= \pi d_{n+1} \,.\, n_{n+1}, \text{ etc.} \\ v_{\min} &= \pi d_{n+1} \,.\, n_n \\ &= \pi d_{n+2} \,.\, n_{n+1}, \text{ etc.} \\ \frac{n_{n+1}}{n_n} &= \frac{v_{\max}}{v_{\min}} = \text{constant.} \end{aligned}$$

In other words, in a range of spindle speeds which allows each diameter to be machined with a cutting velocity of not more than a specified value $v_{\max}$, and not less than a specified value $v_{\min}$ the available spindle speeds must be arranged in a geometric progression with the ratio $\varphi = v_{\max}/v_{\min}$.

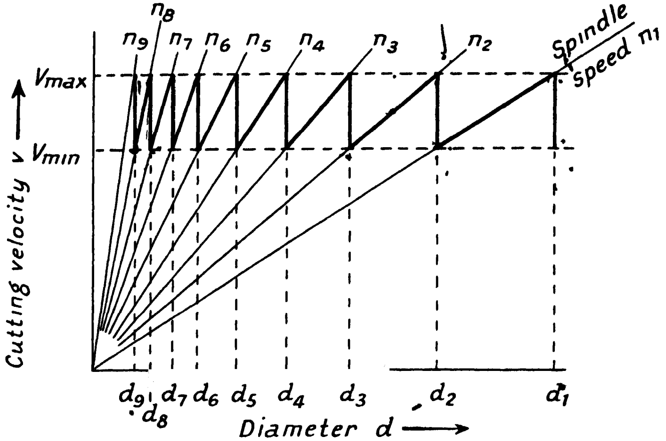


Fig. 1.2. Spindle speeds in geometric progression

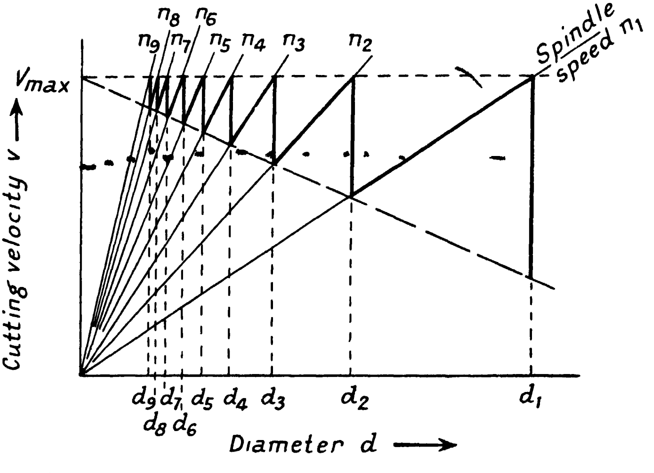


Fig. 1.3. Spindle speeds in arithmetical progression

The diagram, Fig. 1.2, often called the "saw diagram", gives a picture of the conditions; it shows the rather wide gap at the higher end and the larger number of available speeds at the lower end of the diameter range. This is even more pronounced in an arithmetical progression of spindle speeds (Fig. 1.3) which has no constant bottom limit v_{min} and in which the possibility of obtaining economical cutting conditions becomes more and more remote with increasing diameters.

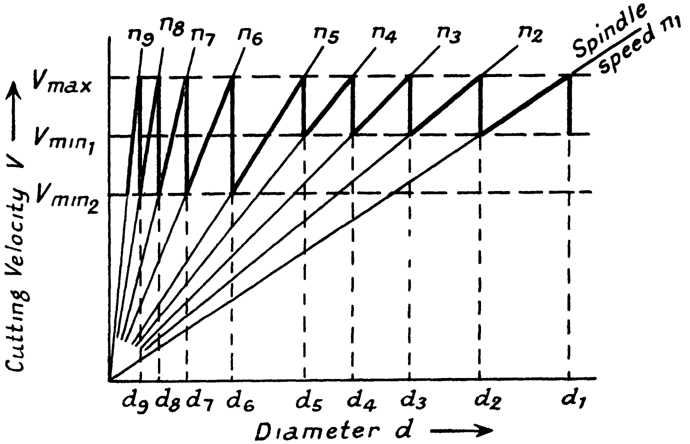


Fig. 1.4. Spindle speeds in two geometric progressions

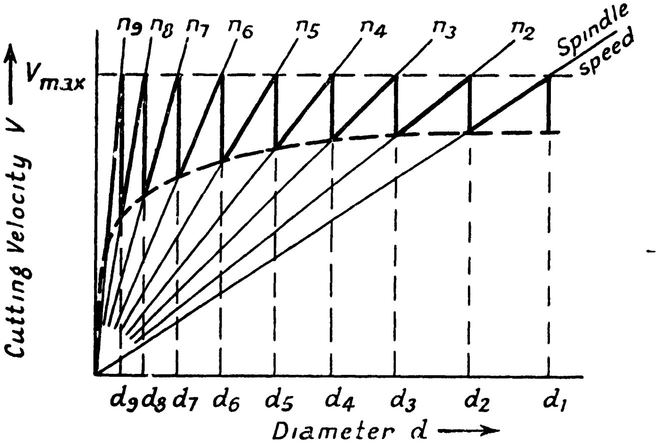


Fig. 1.5. Spindle speeds in logarithmic progression

It has been suggested to use a selected speed range made up from several geometric progressions with different ratios (different values of $v_{\min}$ and therefore of $v_{\max}/v_{\min}$) (Fig. 1.4).

Another suggestion* advocates the use of a range of logarithmic progression in which the value $v_{\max}/v_{\min}$ is a function of the diameter (Fig. 1.5). The use of geometrical progressions has already been accepted internationally in the establishment of "preferred

---

* M. Kronenberg *Grundzuge der Zerspanungslehre* (2nd edn., Springer, Berlin, 1954).

TABLE 1.2. STANDARD SPINDLE SPEEDS (UNDER LOAD)

$\phi =$						$\phi =$						$\phi =$					
1·12	1·25	1·4	1 6	1·6	2	1·12	1·25	1·4	1·6	1·6	2	1·12	1 25	1·4	1·6	1·6	2
10						100						1000		1000			
11·2	11·2	11·2		11·2	11 2	112	112			112		1120	1120			1120	
12·5						125		125				1250					
14	14		14			140	140		140			1400	1400	1400	1400		1400
16		16				160						1600					
18	18			18		180	180	180		180	180	1800	1800			1800	
20						200						2000		2000			
22·4	22·4	22·4	22·4		22·4	224	224		224			2240	2240		2240		
25						250		250				2500					
28	28			28		280	280			280		2800	2800	2800		2800	2800
31·5		31·5				315						3150					
35·5	35·5		35·5			355	355	355	355		355	3550	3550		3550		
40						400						4000		4000			
45	45	45		45	45	450	450			450		4500	4500			4500	
50						500		500				5000					
56	56		56			560	560		560			5600	5600	5600	5600		5600
63		63				630						6300					
71	71			71		710	710	710		710	710	7100	7100			7100	
80						800						8000		8000			
90	90	90	90		90	900	900		900			9000	9000		9000		

These ranges can be extended by multiplication by ten or powers of ten.

numbers"*, and the advantages, particularly for the designer, who has to design speed-change mechanisms for standardized ranges, outweigh the arguments in favour of other types of speed ranges. To-day the geometrical progression using standardized ratios and speed values (and also feed rates) in accordance with preferred numbers is used almost all over the world (Table 1.2).

For the general case of a speed-change device (gear box, headstock, etc.) of a machine tool, which produces spindle speeds in a range of standardized geometric progression, let φ be the ratio between two adjacent spindle speeds, N the number of different spindle speeds obtainable, $n_{\max}$ the maximum, $n_{\min}$ the minimum obtainable spindle speed, and R the range of spindle speeds covered by the speed change device. The following relations are valid:

$$R = \frac{n_{\max}}{n_{\min}}$$

$$n_{\max} = n_{\min} \cdot \varphi^{N-1}$$

$$R = \varphi^{N-1}$$

$$\varphi = \sqrt[N-1]{R}$$

These relations are shown graphically in Fig. 1.6 for those values of φ, which are standardized in accordance with the series of preferred numbers with the addition of the values $\varphi = 1{\cdot}4 = \sqrt{2}$ and $\varphi = 2$. These latter values have been added to allow for speed ranges which can be produced by pole changes of a.c. motors. It is a fortunate coincidence that the requirement of including the value 2 in the standardization of speeds can be combined with that of basing the range of preferred numbers on the decimal system (values of φ : $\sqrt[20]{10} \simeq 1{\cdot}12$; $\sqrt[10]{10} \simeq 1{\cdot}25$; $\sqrt[5]{10} \simeq 1{\cdot}6$), because $\sqrt[10]{10} = 1{\cdot}2589$ and $\sqrt[3]{2} = 1{\cdot}2599$, and for the purpose of the standardization $\sqrt[10]{10} \simeq \sqrt[3]{2} \simeq 1{\cdot}25$.

Such a standardization is valuable not only for the designer of machine tools. It is even more important for the production engineer because it enables him to rely on identical speeds (and feeds) being obtainable on any of the standardized machines at his disposal.

SPEED CHANGE MECHANISMS. An analysis of those generally used in machine-tool drives shows that they consist of a combination of some of the following basic devices (Fig. 1.7):

---

* For a short description of this system, *see* Abbot, W.: *The Dimensioning of Engineering Drawings* (Blackie, 1953). *See also* Kienzle, O.: *Normungszahlen* (Springer, Berlin, 1950).

(*a*) *The Cone Pulley Principle*, Fig. 1.7*a*, applied to belt or chain drives.

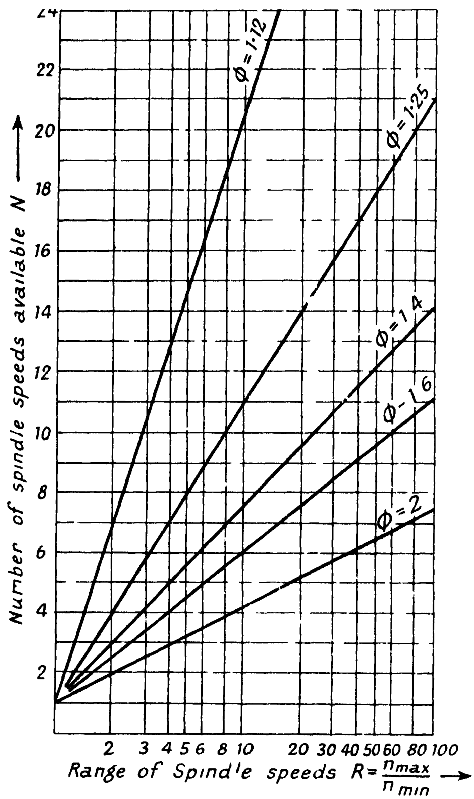


Fig. 1.6

(*b*) *The Sliding Gear Device*, Fig. 1.7*b*. A block of several (usually two or three) gears can be moved along a keyed or splined shaft into different positions in relation to a second block of gears keyed to a shaft parallel to the first one, each position bringing one particular pair of gears into mesh.

(*c*) *The Clutch Arrangement*, Fig. 1.7*c*. One of several (usually two) gears may be coupled to a shaft, the other gears running idle on the shaft.

(*d*) *The Draw Key Drive*, Fig 1.7*d*. One of a row of gears can be keyed to the shaft by means of a sliding key.

(*e*) *The "Norton" Gear*, Fig. 1.7*e*. A gear carrier with a pinion and an intermediate gear can slide along a splined or keyed shaft, the intermediate gear being brought into mesh with a block of gear wheels through a tilting movement of the carrier.

(*f*) In addition, the slip gear arrangement in which gears are fixed to the shafts in question according to the requirements of transmission ratios may be mentioned. This cannot, however, properly be called a change gear as it involves a relatively lengthy fitting operation and is suitable only where the length of the actual machining process is sufficient to justify the time involved; e.g. for long runs in large quantity production or the cutting of screw threads on a lathe and of helical gears on a universal milling machine.

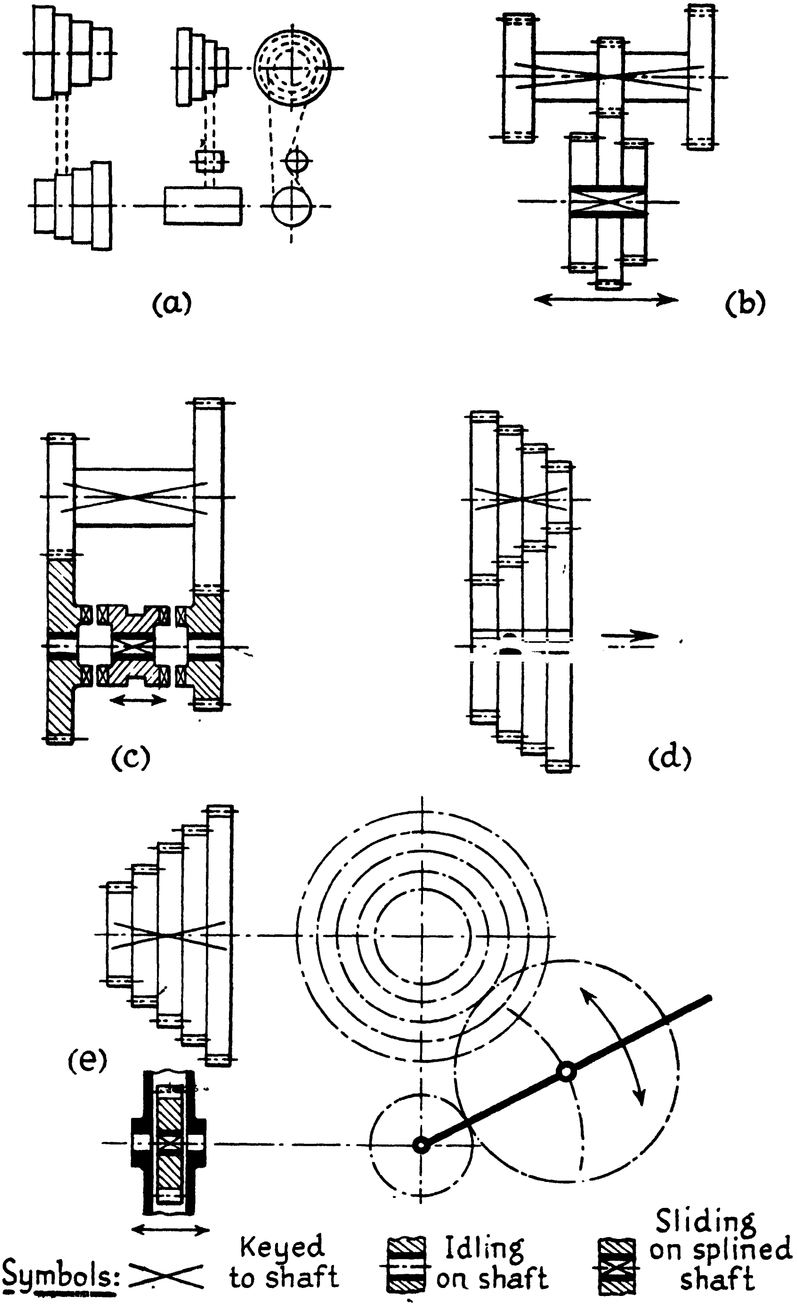
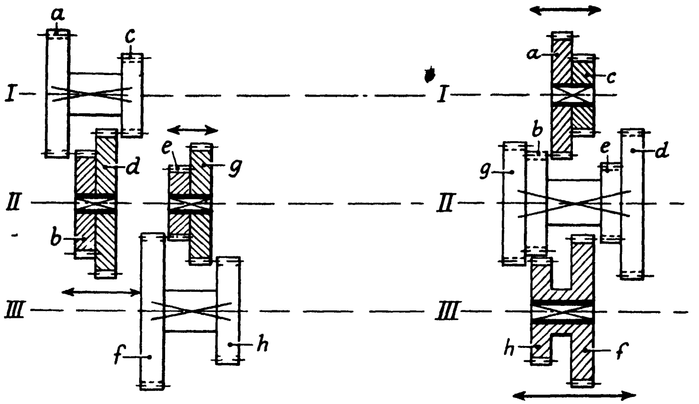


Fig. 1.7. Basic devices of speed change mechanisms



(a) Simple Wide Arrangement (One Splined Shaft)

(b) Space Saving Arrangement (Two Splined Shafts)

(c) Transmission Ratios

(1) $\frac{a}{b}\,\frac{g}{h}$; (2) $\frac{a}{b}\,\frac{e}{f}$, (3) $\frac{c}{d}\cdot\frac{g}{h}$; (4) $\frac{c}{d}\,\frac{e}{f}$

(d) Speed Diagram (Schematic)

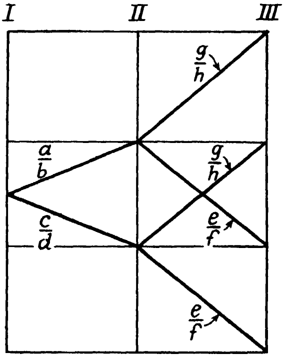


Fig. 1.8. Typical arrangements of a sliding gear speed change mechanism

In the drives mentioned under (*c*) and (*d*) it is important that the clutch or the key are arranged on the driven shaft and not on the driving one, otherwise the idling gears are driven at a very high speed with bad effect on their bearing bushes. The arrangements mentioned under (*d*) and (*e*) are almost exclusively used for feed drives, because they are suitable only for relatively low power transmission.

Considerations of space and ease of operation limit the number of gears which can be used in each of the basic devices mentioned. It is, however, possible to arrange them in series in such a manner as to provide wide ranges of speeds, each basic device offering the possibility of multiplying the speed ratios provided by the preceding or following one (Fig. 1.8).

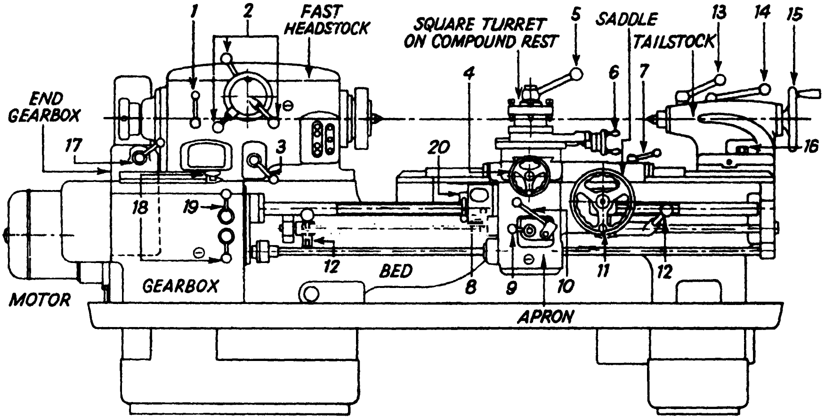
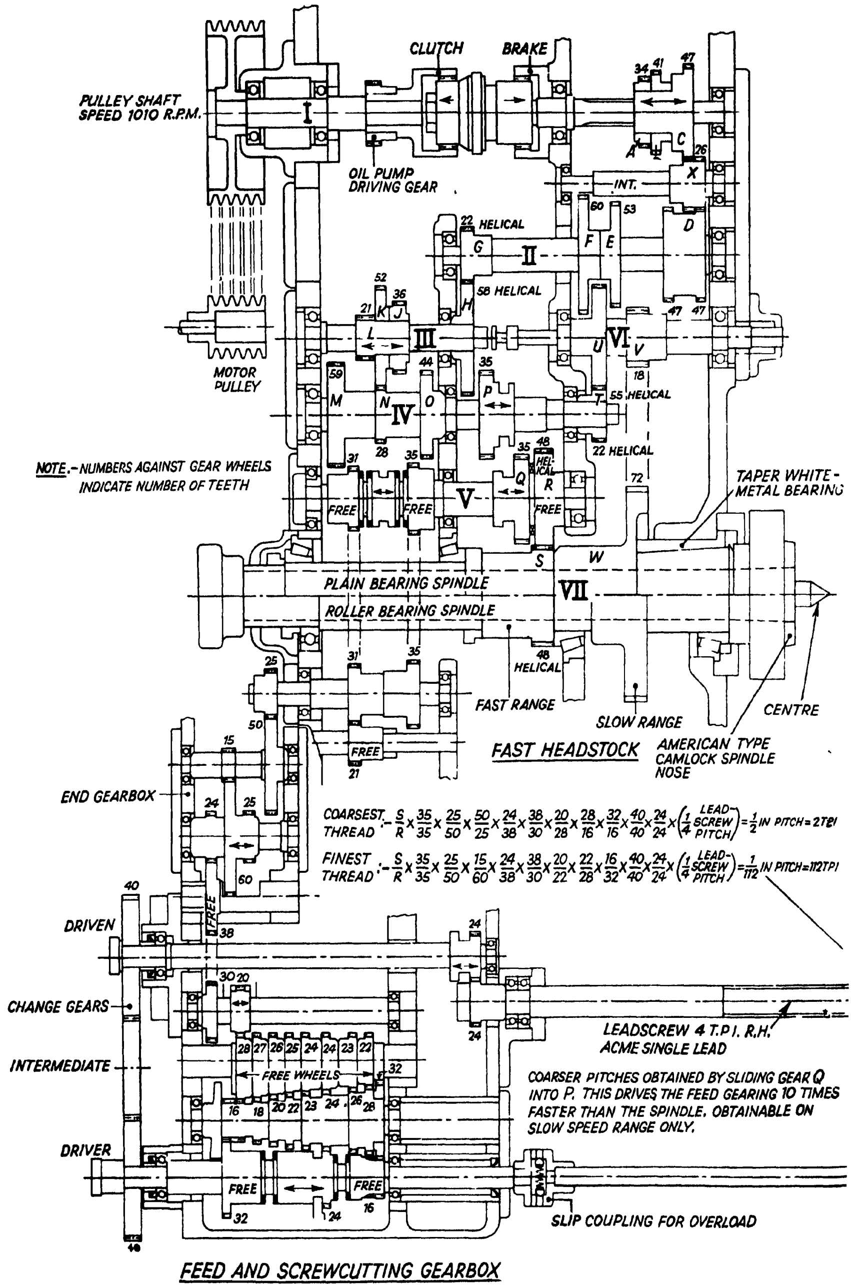


Fig. 1.9 (*a*). Centre lathe

(*Dean, Smith & Grace Ltd., Keighley*)

The specification and design of gear arrangements for new speed-change drives and the analysis and use of existing ones can be greatly facilitated by the use of speed diagrams. The speeds of the various shafts (axes I to VII) of the change gear Fig. 1.9 (*b*) are shown on a logarithmic scale on lines representing the axes. If these lines are drawn equidistant, each slope of a line joining the speeds between any two adjacent axes represents a certain gear ratio, and Fig. 1.10 (*see also* Fig. 1.8) gives a clear picture of the train of gears which has to be brought into operation to obtain a desired speed of the output shaft (VII), in this case the machine spindle.

Among the infinitely-variable speed drives, friction drives and hydraulic gears may be mentioned. Hydraulic gears consist, usually, of a hydraulic pump driven at constant speed by an electric motor,



COARSEST THREAD :- $\frac{S}{R}\times\frac{35}{35}\times\frac{25}{50}\times\frac{50}{25}\times\frac{24}{38}\times\frac{38}{30}\times\frac{20}{28}\times\frac{28}{16}\times\frac{32}{16}\times\frac{40}{40}\times\frac{24}{24}\times\left(\frac{1}{4}\text{ LEAD-SCREW PITCH}\right)=\frac{1}{2}$ IN PITCH = 2TPI

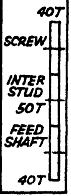
FINEST THREAD :- $\frac{S}{R}\times\frac{35}{35}\times\frac{25}{50}\times\frac{15}{60}\times\frac{24}{38}\times\frac{38}{30}\times\frac{20}{22}\times\frac{22}{28}\times\frac{16}{32}\times\frac{40}{40}\times\frac{24}{24}\times\left(\frac{1}{4}\text{ LEAD-SCREW PITCH}\right)=\frac{1}{112}$ IN PITCH = 112TPI

COARSER PITCHES OBTAINED BY SLIDING GEAR Q INTO P. THIS DRIVES THE FEED GEARING 10 TIMES FASTER THAN THE SPINDLE. OBTAINABLE ON SLOW SPEED RANGE ONLY.

Fig. 1.9 (*b*). Centre lathe change gear

(*Dean, Smith & Grace Ltd., Keighley*

SPINDLE SPEEDS	FORWARD	REVERSE
$\frac{A}{F}\times\frac{G}{H}\times\frac{L}{M}\times\frac{T}{U}\times\frac{V}{W}$	7·726	
$\frac{B}{E}\times\frac{G}{H}\times\frac{L}{M}\times\frac{T}{U}\times\frac{V}{W}$	10·54	
$\frac{C}{D}\times\frac{G}{H}\times\frac{L}{M}\times\frac{T}{U}\times\frac{V}{W}$	13·63	13·63
$\frac{A}{F}\times\frac{G}{H}\times\frac{J}{O}\times\frac{T}{U}\times\frac{V}{W}$	17·75	
$\frac{B}{E}\times\frac{G}{H}\times\frac{J}{O}\times\frac{T}{U}\times\frac{V}{W}$	24·24	
$\frac{C}{D}\times\frac{G}{H}\times\frac{J}{O}\times\frac{T}{U}\times\frac{V}{W}$	31·34	31·34
$\frac{A}{F}\times\frac{G}{H}\times\frac{K}{N}\times\frac{T}{U}\times\frac{V}{W}$	40·31	
$\frac{B}{E}\times\frac{G}{H}\times\frac{K}{N}\times\frac{T}{U}\times\frac{V}{W}$	55·03	
$\frac{C}{D}\times\frac{G}{H}\times\frac{K}{N}\times\frac{T}{U}\times\frac{V}{W}$	71·15	71·15
$\frac{A}{F}\times\frac{G}{H}\times\frac{L}{M}\times\frac{P}{Q}\times\frac{R}{S}$	77·28	
$\frac{B}{E}\times\frac{G}{H}\times\frac{L}{M}\times\frac{P}{Q}\times\frac{R}{S}$	105·5	
$\frac{C}{D}\times\frac{G}{H}\times\frac{L}{M}\times\frac{P}{Q}\times\frac{R}{S}$	136·4	136·4
$\frac{A}{F}\times\frac{G}{H}\times\frac{J}{O}\times\frac{P}{Q}\times\frac{R}{S}$	177·6	
$\frac{B}{E}\times\frac{G}{H}\times\frac{J}{O}\times\frac{P}{Q}\times\frac{R}{S}$	242·4	
$\frac{C}{D}\times\frac{G}{H}\times\frac{J}{O}\times\frac{P}{Q}\times\frac{R}{S}$	313·4	313·4
$\frac{A}{F}\times\frac{G}{H}\times\frac{K}{N}\times\frac{P}{Q}\times\frac{R}{S}$	403·1	
$\frac{B}{E}\times\frac{G}{H}\times\frac{K}{N}\times\frac{P}{Q}\times\frac{R}{S}$	550·4	
$\frac{C}{D}\times\frac{G}{H}\times\frac{K}{N}\times\frac{P}{Q}\times\frac{R}{S}$	711·5	711·5
REVERSE SPEEDS THROUGH GEAR "X"		

POSITION	1	2	3	4	5	6	7	8	
THREADS PER INCH	2	2¼	2½	2¾	2⅞	3	3¼	3½	CHANGE GEARS
	4	4½	5	5½	5¾	6	6½	7	
	8	9	10	11	11½	12	13	14	
	16	18	20	22	23	24	26	28	
	32	36	40	44	46	48	52	56	
	64	72	80	88	92	96	104	112	
	FOR CROSS FEEDS DIVIDE THE NUMBERS BELOW BY 2								
LONGITUDINAL FEEDS IN INCHES PER REV.	·0700	·0620	·0560	·0510	·0490	·0470	·0430	·0400	
	·0350	·0310	·0280	·0250	·0240	·0235	·0215	·0200	
	·0175	·0160	·0140	·0125	·0120	·0116	·0107	·0100	
	·0087	·0080	·0070	·0063	·0060	·0058	·0054	·0050	
	·0044	·0040	·0035	·0032	·0030	·0029	·0027	·0025	
	·0022	·0020	·0017	·0016	·0015	·0014	·0013	·0012	

SCREW PITCHES IN INCHES

COARSE PITCHES							NORMAL PITCHES									
SET TO T.P.I.			CHANGE GEARS				SET TO T.P.I.						CHANGE GEARS			
2	4	8	N	P	R	S	2	4	8	16	32	64	N	P	R	S
	3½	1¾	63	40 INTER		45	1	½	¼	⅛	1/16	1/32	63	35	50	45
	3¼	1⅝	65	45 INTER		50	15/16	15/32					60	40	50	40
	3	1½	60	45 INTER		50	⅞	7/16	7/32				63	40	50	45
	2¾	1⅜	55	45 INTER		50	13/16	13/32					65	45 INTER		40
5	2½	1¼	40	55 INTER		40	¾	⅜	3/16	3/32			60	50 INTER		40
4½	2¼	1⅛	45	55 INTER		50	11/16	11/32					55	50 INTER		40
4	2	1	40	55 INTER		50	⅝	5/16	5/32				50	60 INTER		40
3¾	1⅞	15/16	45	55 INTER		60	9/16	9/32					45	60 INTER		40

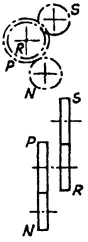
FOR PITCHES NOT SHOWN ABOVE:- $\frac{N}{S}$ OR $\frac{N\times R}{P\times S}=\frac{\text{PITCH REQUIRED}\times\text{T.P.I. SET FOR}}{1\ (\times 10\ \text{FOR COARSE PITCH})}$

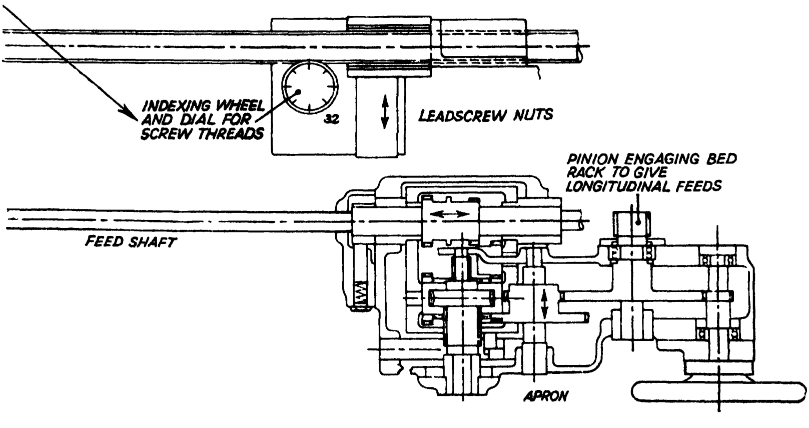
SCREW PITCHES IN MILLIMETRES

SET LEVERS TO THESE T.P.I.									CHANGE GEARS			
4	8	16	2	4	8	16	32	64				
COARSE PITCH			NORMAL PITCHES						N	P	R	S
130	65			13	6·5	3·25			63	40	65	50
125			25	12·5	6·25				63	40	50	40
120	60	30	24	12	6	3	1·5	·75	63	40	60	50
110	55		22	11	5·5				63	40	55	50
100	50	25	20	10	5	2·5	1·25		63	45 INTER		40
90	45		18	9	4·5	2·25			63	40	45	50
80	40	20	16	8	4	2	1	·5	63	40 INTER		50
75			15	7·5	3·75				63	40	45	60
70	35		14	7	3·5	1·75			63	40	35	50

FOR PITCHES NOT SHOWN ABOVE.- $\frac{N}{S}$ OR $\frac{N\times R}{P\times S}=\frac{63\times\text{PITCH REQ'D}\times\text{T.P.I. SET FOR}}{1600\ (\times 10\ \text{FOR COARSE PITCH})}$

CHANGE GEARS




INDEXING WHEEL AND DIAL FOR SCREW THREADS
32
LEADSCREW NUTS
PINION ENGAGING BED RACK TO GIVE LONGITUDINAL FEEDS
FEED SHAFT
APRON

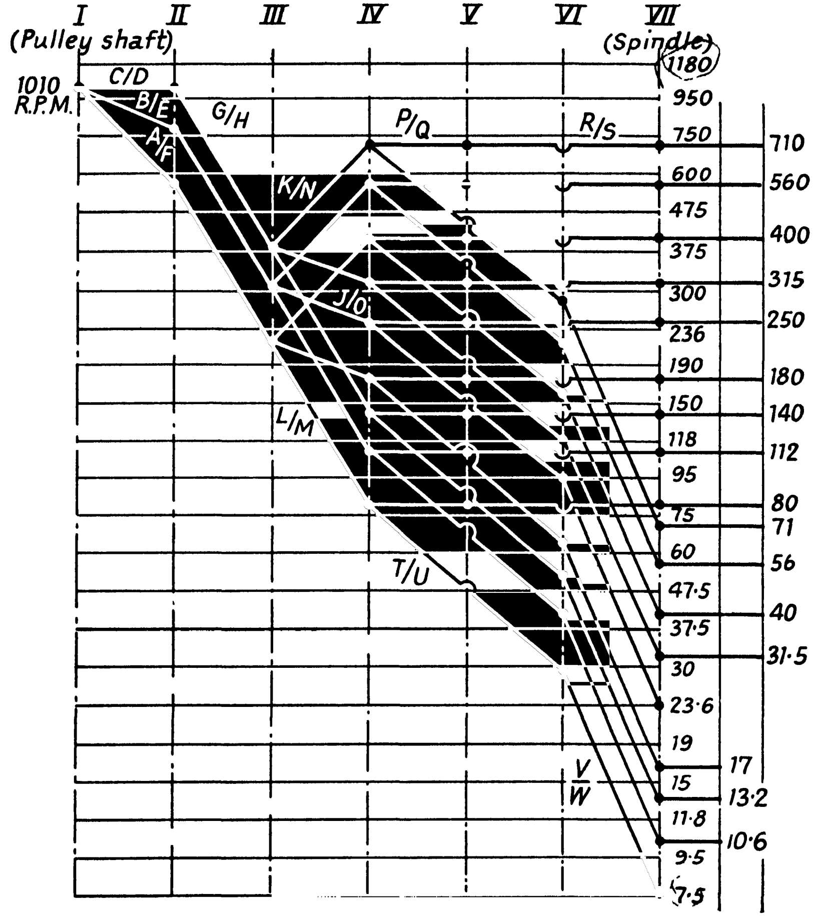


Fig. 1.10. Spindle speed diagram for the centre lathe shown in Fig. 1.9

and a hydraulic motor, the speed of which depends upon the oil delivery of the pump and the displaceable oil volume in the motor.

Pumps and motors are usually of similar design, working on the principle of either vanes, Fig. 1.11, radial pistons, Fig. 1.12, or axial pistons, Fig. 1.13. In most arrangements volumetric displacement of either the pump or the motor or both is adjustable by varying the eccentricity (Fig. 1.11 and Fig. 1.12) or the angle between driving shaft and piston axis (Fig. 1.13) and, correspondingly, the delivery of the pump and the speed of the motor are infinitely variable.

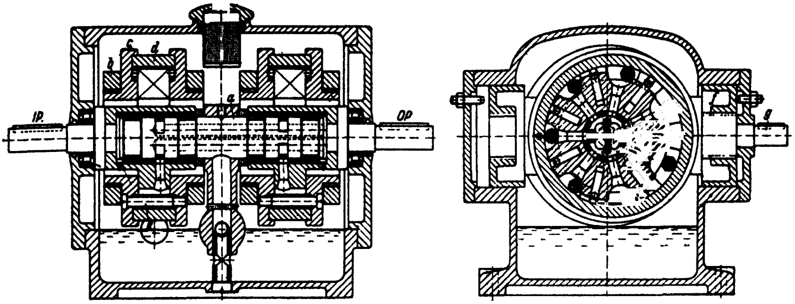


Fig. 1.11. Vane pump and motor*

IP, input. *OP*, output. *a*, fixed pin. *b*, carrier frame. *c*, cover. *d*, guide ring. *e*, fixing screws. *f*, guide for carrier frame. *g*, screw for adjusting eccentricity and with it pump delivery

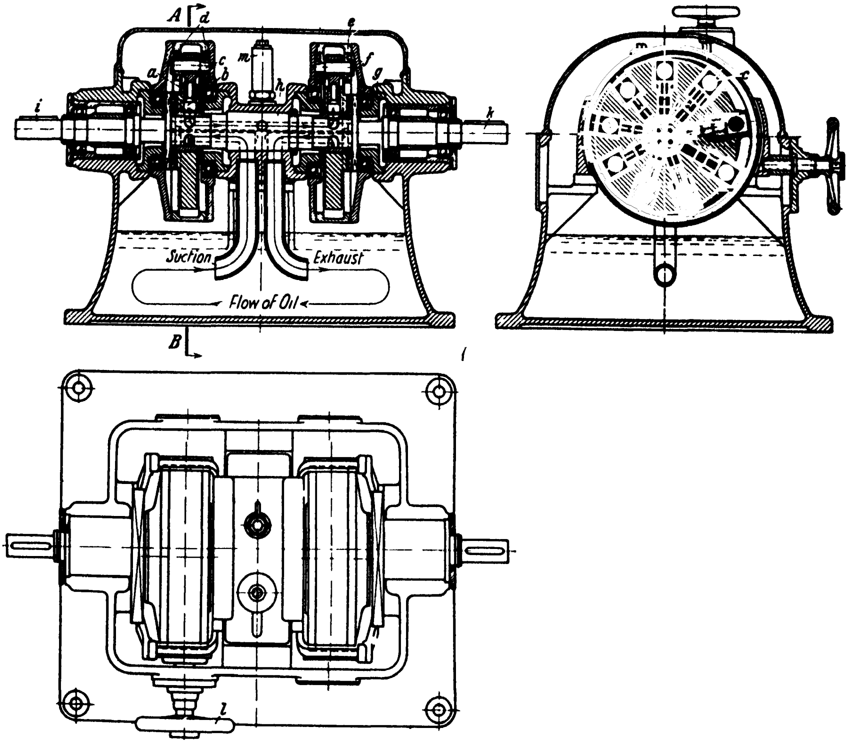


Fig. 1.12. Radial piston pump and motor*

a, rotating body. *b*, pistons, *c*, cross heads. *d*, rollers. *e*,*f*, movable housing containing roller guides. *g*, adjusting frame. *h*, fixed central pin. *i*, driving shaft of pump (input). *k*, driven shaft of motor (output). *l*, hand wheel for adjustment of eccentricity and with it pump delivery. *m*, overload valve.

* From Schlesinger, G.: *Die Werkzeugmaschinen* (Springer, Berlin, 1936).

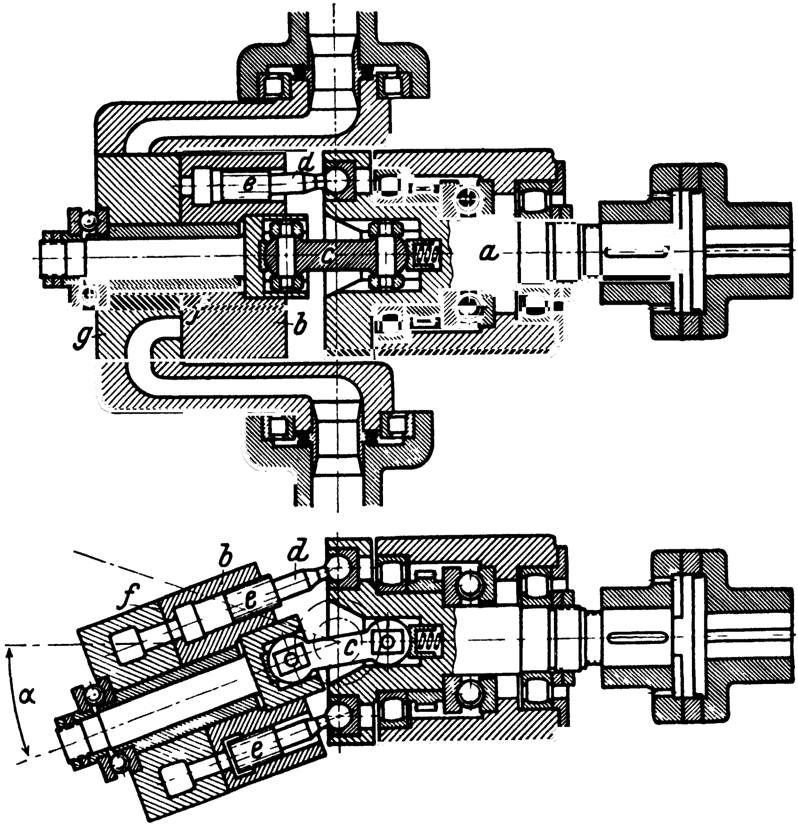


Fig. 1.13. Principle of axial piston pump*

a, driving shaft and piston rod carrier. *b*, cylinder body rotating with (*a*). *c*, universal joint link between (*a*) and (*b*). *d*, piston rods. *e*, pistons. *f*, guiding thrust surface for (*b*). *g*, tilting frame containing surface (*f*). α, adjustable angle which determines piston stroke and with it pump delivery.

The difficulty of a certain unavoidable amount of slipping in these drives is overcome in the P.I.V. (Positive, Infinitely Variable) gear, Fig. 1.14. This consists of a chain drive with ingeniously adjustable semi-internal sprocket wheels.

Feed Drives. Feed movements may be continuous (lathe, drilling machine, boring machine, milling machine, cylindrical

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* From Schlesinger, G. : *Die Werkzeugmaschinen* (Springer, Berlin, 1936).

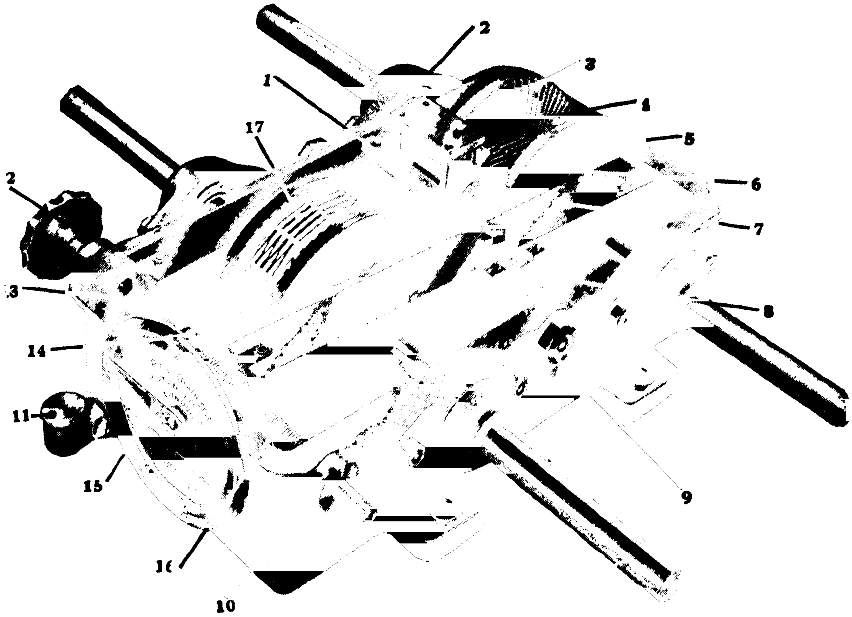

Fig. 1.14. P.I.V. gear

1. Shoe assembly. 2 Radial ball bearings 3. Patent P.I.V. wheel face. 4. Shoe guide 5. Cast iron wheel flange. 6. Ball thrust bearing. 7. Operating levers. 8. Chain tightening cam. 9. Chain tightening screw and locking plate 10 Alignment fitting. 11. Oil filler and level indicator. 12. Speed control hand wheel. 13. Control bracket. 14. Speed limiting nut. 15. Speed indicator. 16. Control screw. 17. Patent P.I.V. chain.

(*Stone-Wallwork Ltd., London*)

grinding machine) or intermittent (planer, shaper, surface grinder). The magnitude of the feed rate, together with the depth of cut, determines the chip section and with it the volume of metal removed. The effect of the feed rate on the quality of macro-finish (not surface finish in the accepted sense, which is micro-finish) is the main factor which influences the selection of the maximum feed rate for a particular operation (Fig. 1.15). With a relatively high feed rate a high quality finish cannot be obtained except by using overlapping cuts with broad tools (Fig. 1.16).

When the feed movement is parallel to the axis of rotation (turning, drilling, boring, cylindrical grinding) the feed rate is usually measured in inches per revolution of the rotating part (tool or workpiece). When the direction of the feed movement is at right angles to the axis of rotation (milling, surface grinding) its rate is usually measured in inches per minute.

The pure machining time of an operation depends upon the rate of feed: $\text{Time (min.)} = \dfrac{\text{Length of cut (in.)}}{\text{Feed rate (in./min.)}}$ Where this rate is set in in./min. the machining time is independent of the cutting speed, and although the latter, together with the feed rate, influences the loading conditions on the tool (e.g. the load per tooth of a milling cutter) an accurate attainment of the highest possible cutting velocity is not essential from the point of view of speed of production.

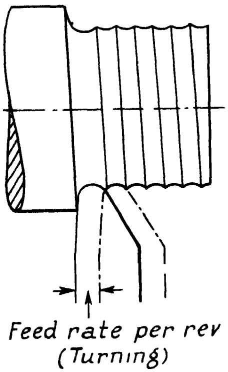

Fig. 1.15

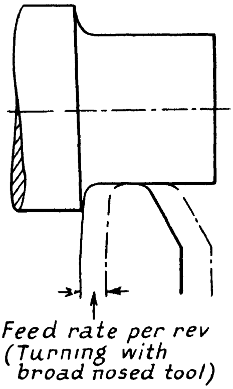

Fig. 1.16

When the feed rate is set in in./rev. (lathe, drilling machine, etc.) or in in./cutting stroke (planer, shaper) the feed rate per minute and with it the speed of operation depends upon the cutting speed (Feed/min. = Feed/rev. × rev./min.) In such cases it is, therefore, most essential for maximum output, to run as closely as possible to the highest permissible cutting speed, and to achieve this aim the speed range of the change gear should be very finely stepped. For this reason spindle-drive gear boxes of lathes and drilling machines usually provide much finer speed ranges than, e.g., spindle-drive gear boxes of milling machines, the feed gear boxes of which, on the other hand, offer very finely stepped ranges,

Feed movements are mostly straight line rather than rotating motions. Conversion from the rotation of the motor and gear box shafts into a straight line movement is usually obtained by: (*a*) rack and pinion; (*b*) screw and nut; (*c*) hydraulic cylinder and piston.

The last is particularly advantageous when frequent reversing is required (grinding machines) because of the shockless action which can be obtained. In operations causing pulsating, impact and intermittent loads on the hydraulic system (milling and particularly down-cut milling) difficulties may be encountered due to the compressibility of the hydraulic fluid and possible variation in oil viscosity. Special precautions have to be taken, and steadying devices (hydraulic locking) provided to overcome the difficulties. With a simple overload valve arrangement, feeding against rigid stops is possible (*see* below) but the movement obtained is not positively related to the revolutions of a spindle.

Accurate positive relationship between spindle-drive mechanism and feed movement is important not only in screw cutting (accuracy of pitch). In diamond turning operations to a high degree of surface finish and with feed rates of 0·0005 in./rev. a deviation of only 0·0001 in./rev. means an irregularity of 20 per cent which is clearly visible and spoils the appearance of the mirror finish. Both rack-and-pinion and leadscrew-nut mechanisms provide a positive spindle-feed relationship. Unless special design and manufacturing precautions are taken, however, the rack-and-pinion drive, usually incorporating a pinion with a small number of teeth, may produce marks which are due to sliding velocity variations caused by the unfavourable meshing conditions between the teeth of the rack and the pinion (usually only one or two teeth in mesh). A perfectly smooth drive can be obtained with the leadscrew-nut mechanism, which is, however, relatively expensive and slower in operation unless special design arrangements are provided.

A very essential part of feed-driving devices is an accurate stopping mechanism which is most important when turning or grinding against a shoulder, or milling slots to an exact length, etc. If a high degree of stopping accuracy is required, the ordinary mechanism which disengages dog clutches or knocks a pair of sliding gears out of mesh, may not be satisfactory.

In such cases, rigid stops, often adjustable by means of micrometer screws, are frequently used in such a manner that an overload device comes into action (at first slipping and then completely disengaging the driving mechanism) as soon as the stop prevents further movement. A typical example is the dropping-worm mechanism in which a bracket carrying the worm-shaft bearings in the apron swings the feed driving worm out of its engagement with the worm wheel, thus disconnecting the drive. Unless special design precautions are taken, the value of such devices may be limited by the fact that during the process of disengagement the whole mechanism is often in a state of high elastic tension. This is released as soon as disengagement has taken place, and the resilience of the previously strained members of the mechanism causes the driven part (slide, saddle, etc.) to jump back slightly, resulting in sometimes inadmissible tool marks on the machined surface.

Power Requirements. The power requirements of the various drives depend upon the cutting force component in the direction of the movement under consideration, and the corresponding velocity. In turning operations, the component force in the direction of the cutting movement is greater than that in the direction of the feed movement (ratio about 4 : 1 to 6 : 1) and the velocity of the relative cutting movement between tool and component is far higher than the feed rate.

Take, for example, the rough turning of a 4 in. diameter mild steel cylindrical bar at a cutting velocity of about 320 ft./min. (300 r.p.m.), depth of cut $\frac{1}{8}$ in., feed 0·033 in. rev. The tangential cutting force component will be approximately 1200 lb.; the component in the direction of the feed movement approximately 250 lb. The velocity in the direction of the feed movement is

$$0{\cdot}033 \times 300 = 10 \text{ in./min.} \simeq 0{\cdot}8 \text{ ft./min.}$$

The net horsepower required for the cutting movement is then

$$hp_C = \frac{1200 \times 320}{33000},$$

that required for the feed movement is

$$hp_F = \frac{250 \times 0{\cdot}8}{33000}$$

The ratio between the two is

$$\frac{hp_F}{hp_C} = \frac{250 \times 0{\cdot}8}{1200 \times 320} = 0{\cdot}0005$$

$$= 0{\cdot}05 \text{ per cent.}$$

In slab milling operations at a cutting depth which is relatively small compared with the cutter diameter the cutting force components in the direction of the cutting (tangential) and feed movement are approximately identical. The ratio of the power requirements is, therefore, approximately equal to that between the feed rate and the cutting velocity, i.e. in the order of magnitude of not more than 40 in./min. to 200 ft./min (2400 in./min).

Therefore $\frac{hp_F}{hp_C} = \frac{40}{2400} = 0{\cdot}017 = 1{\cdot}7$ per cent.

Considering the unavoidably low mechanical efficiency of the usual feed drive mechanisms, especially in lathes, it is usual to allow for a power input of 3–4 per cent of the cutting power for the feed drive of a lathe, and 15–20 per cent of the cutting power for the feed drive of a milling machine.

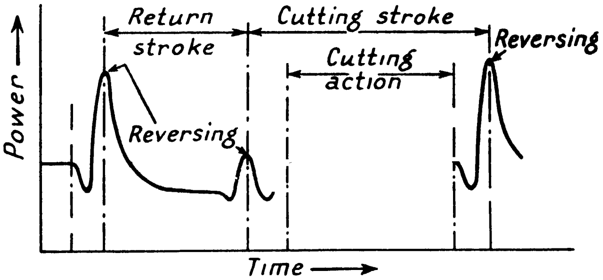

Fig. 1.17. Oscillograph record of the power consumption for a planing operation

It is particularly important to make a careful estimate of power requirements when very high cutting velocities are contemplated, even if the actual cutting forces are relatively and misleadingly small. An example is the case of grinding operations where forces are very small but cutting velocities of 80 ft. /sec. and more are used.

In the planing machine, power conditions are entirely different from those mentioned before. The feed movement, usually ratchet operated, takes place during the return stroke of the table, but considerable power is required to reverse the table and its drive. The mechanical efficiency of the planing machine is low because the return stroke and the reversing action do not directly result in any useful work. The efficiency grows with increasing working stroke because of the increasing proportion of useful to total work done. Various means of reducing the energy requirements for reversing the table movement have been introduced, such as buffer springs, reduction of reversing masses, infinitely variable speed drives (Ward-Leonard drive), etc. The proportions of energy required for the four phases of table movement, cutting stroke, reversing, return stroke, reversing, can be seen from the oscillograph record of a planing operation (Fig. 1.17).*

Performance. Machine tools in the production workshop are expected to produce, at an economic speed and within specified limits, surfaces of workpieces of required shape, dimensional accuracy and quality of surface finish.

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* From Schlesinger, G.: *Die Werkzeugmaschinen* (Springer, Berlin, 1936).

Speed of production requires machines which

1. make full use of the tools and tool materials available for high velocity cutting conditions,
2. cope with the power required for a high rate of metal removal,
3. are easily and quickly set, operated and controlled, thus keeping non-productive operation times short.

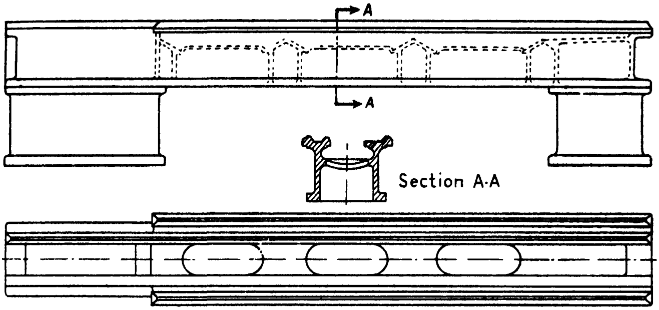
The speed of production must not, however, interfere with the quality of work, especially in finishing operations. The accuracy of shape and dimensions of the finished workpiece depend on the relative positions between tool and workpiece material at every moment of the operation, and this in turn depends on the holding and guiding devices that determine the positions of those parts on which tool and workpiece are located. Not only must these devices be accurately produced and aligned, but displacements due to play and distortion under the effect of external forces (cutting forces, weight of the workpieces, clamping forces) must also be kept within permissible limits. Furthermore, the machine tool and its component parts must be rigid enough to prevent high machining speeds causing undesirable vibrations, as these would result in poor surface finish.

To ensure the required performance, the parts of a machine tool must, therefore, possess (*a*) strength to withstand the cutting forces; (*b*) stiffness against deformation under load; (*c*) rigidity against vibrations; (*d*) provisions which ensure that the accuracy of relative location and alignment of all component parts is maintained throughout the working range of the machine.

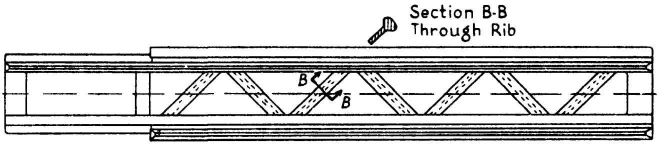
Some fundamental considerations will now be examined for the following elements of machine tools: (1) The bed, body or upright. (2) The slides and slideways for straight line movements. (3) The main spindle in its bearings. (4) The arrangement of operating, setting and control devices (handles, levers, etc.)

(1) MACHINE BODY. Whether the body of the machine is a bed (lathe, grinding machine), an upright (milling or drilling machine) or a combination of both (horizontal borer, planer) it is the basic structure of the machine tool. On it the vital parts of the machine are either rigidly fastened in their correct positions, or guided along the intended paths of movement in such a manner that they are accurately aligned in relation to each other and kept so

during the operation of the machine, i.e. under its working load. The stressing conditions of most machine tool bodies are rather complex, but generally a combination of bending and torsion will be found. While the actual stresses are usually low (it is stiffness rather than strength which determines the design) every effort is made to reduce distortion to a minimum. For this reason the almost completely closed box section which gives the best stiffness in torsion, and is also satisfactory in bending, is favoured more and more in modern designs.



(a) Old Design *(Straight Ribbing)*



(b) Newer Design *(Diagonal Ribbing)*

Fig. 1.18. Typical designs of lathe beds

If stiffness were the only decisive factor, totally-closed sections could be employed everywhere, but this would often interfere with the necessary facilities for easy swarf removal, e.g. in a lathe bed, or with the need for accessibility where gear drives, etc. are housed inside the machine body. It is often necessary, therefore, to provide open sections, or at least openings, in the machine body, and the weakening thus caused must be counteracted by stiffening devices. The most effective design is the diagonal arrangement of stiffener webs. Experiments carried out on a lathe bed showed* that considerable increase in torsional stiffness was obtained when changing from the old design (Fig. 1.18*a*) to the new one (Fig. 1.18*b*). A compromise in which one side of a bed, partially box-sectioned, is used as a chute for cuttings is shown in Fig. 1.19.

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* *See* Peters, *Werkstattstechnik* (1920).

The requirements of stiffness and rigidity in precision grinding-machine beds are more severe than those of lathe beds, which are usually supported by two or sometimes three legs (Fig. 1.20). These form a connecting link between bed and foundation thus enabling the foundation to take its share in stiffening the bed. Such an arrangement would be unsatisfactory for grinding machines. The bed of the grinding machine must not be rigidly fixed to its foundation because of possible straining and distortion due to changes in temperature; the qualities of stiffness and rigidity must be embodied in the machine bed itself. Grinding machine beds are usually designed as deep box sections, with few openings, to give the maximum rigidity (Fig. 1.21). To avoid restraining reactions, which might be caused by the foundation through the foundation bolts, the grinding machine bed is usually freely supported at several points, only three if possible (Fig. 1.22), to obtain a statically determinate system. For levelling purposes adjustable wedge boxes are often used as supports.

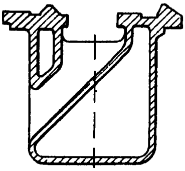

Fig. 1.19. Box-section of lathe bed

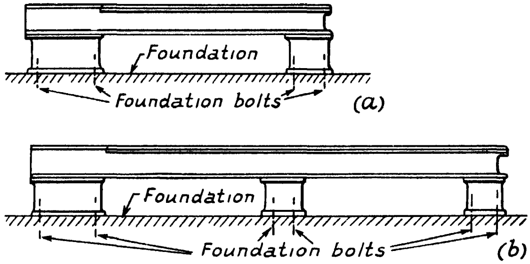

Fig. 1.20. Installation of lathe beds

Any deviations from straightness in the beds of long grinding and planing machines, which have to produce highly accurate work, have to be watched and corrected regularly. For this reason they are often supported by adjustable wedge boxes at intervals of about three feet (Fig. 1.23).

Closed box sections are generally used in the uprights of milling or boring machines which are acting as cantilevers clamped at the base and free at the top, unless special bracing devices make the upright of the machine, the overarm and outer stay into a closed frame, with resulting high stiffness and rigidity. Such an arrangement, however, impairs the manœuvrability of the machine and is, therefore,

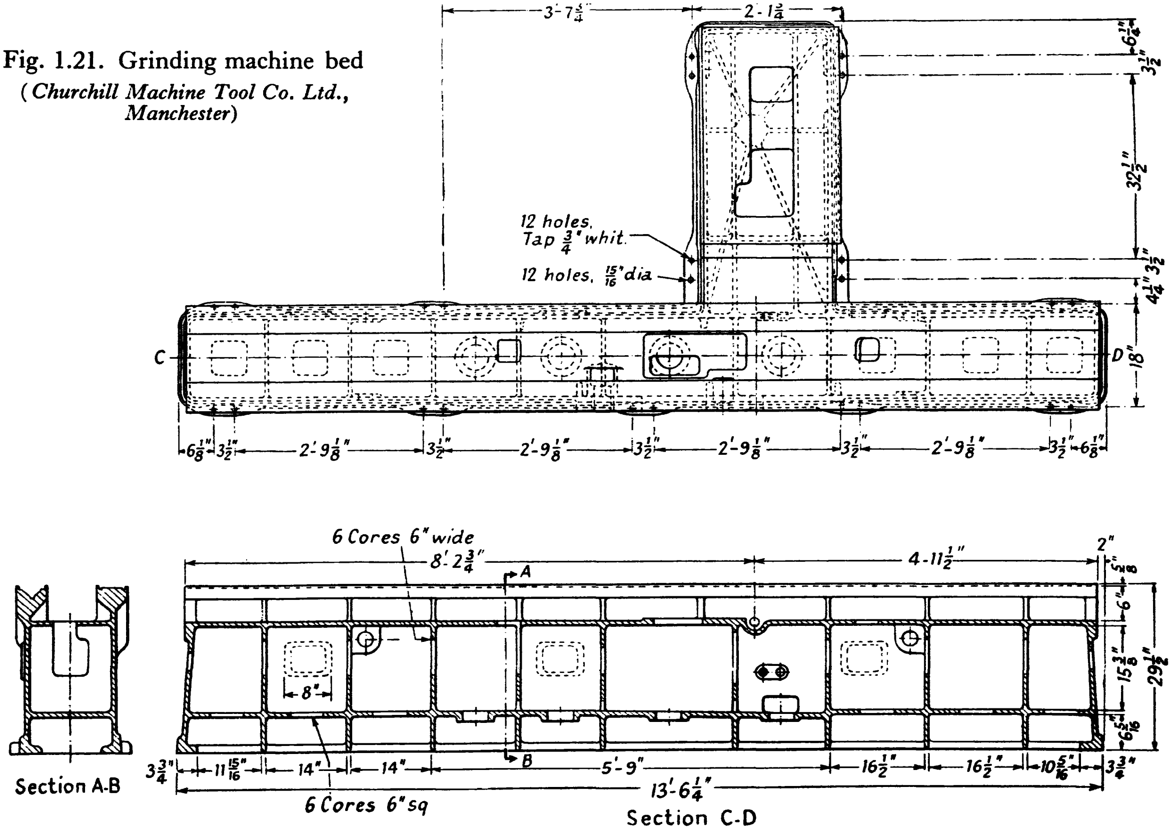

Fig. 1.21. Grinding machine bed
(*Churchill Machine Tool Co. Ltd., Manchester*)

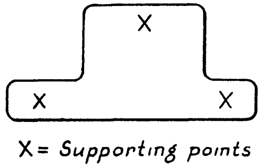

Fig. 1.22. Inverted plan view of grinding machine bed

rarely used in radial drilling machines where free and easy adjustment of the drill position in height, along the radial arm, and around the column as a fulcrum is most desirable

In radial drill machines the two superimposed cantilevers of the column fastened to the base, and the radial arm fastened to the column, militate against stiffness and rigidity, and it is important to bear their exact stiffness conditions in mind when judging the different designs on the market.

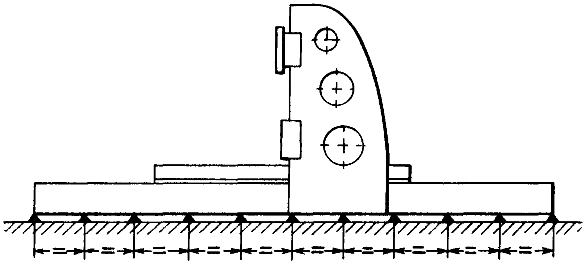

Fig. 1.23. Arrangement of supports for planing machine bed

The two basic designs are: (*a*) in which the radial arm swings around and moves up and down a large column (Fig. 1.24), (*b*) in which the radial arm slides up and down an intermediate sleeve which in turn rotates around a slightly weaker column (Fig. 1.25). Both designs can be justified by the designer and have advantageous features, but to the user it is important that he should appreciate the conditions governing the stiffness of the machine as a whole at different heights of the radial arm. Fig. 1.26 shows the result of an analytical study.* In the arrangement in Fig. 1.24 the maximum deflection of the drilling spindle axis occurs when the radial arm is at its top position, and the minimum when the radial arm is at its bottom position. In the arrangement shown in Fig. 1.25, on the other hand, the minimum deflection occurs when the radial arm is half-way up the column. It is necessary to bear this difference in mind, not only in relation to the type of work for which the machine is to be employed, but also when considering the results of

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* Schlesinger, G. and Koenigsberger, F.: "Colonne unique contre colonne et douille des machines à percer radiales", *La Machine Moderne*, Paris, July 1936.

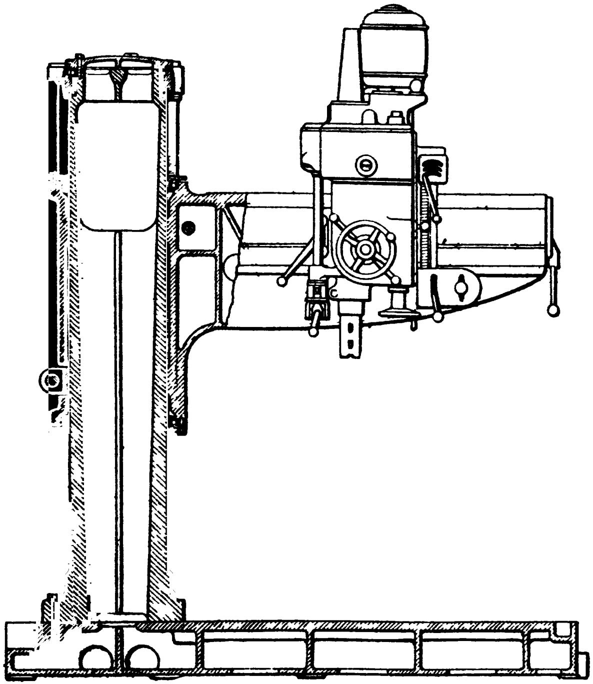

Fig. 1.24. Radial drilling machine

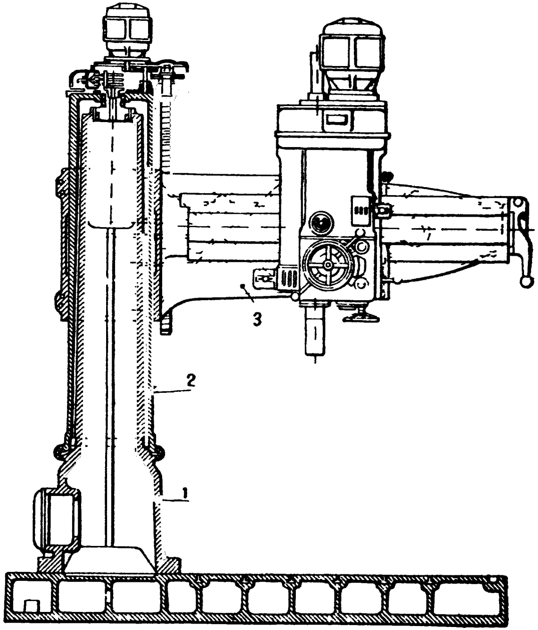

Fig. 1.25. Radial drilling machine with column and sleeve

1, column. 2, sleeve. 3, radial arm.

stiffness measurements during acceptance tests, because the usual specification of testing the machine under load with the radial arm at mid-height is more favourable to the arrangement shown in Fig. 1.25 than it is to that shown in Fig. 1.24.

(2) Slideways. The slideways serve for locating and aligning stationary parts of the machine (bed, upright, headstock, etc.) and for aligning and guiding the parts (carrying tool or workpiece) which have to move, usually along straight lines, in the direction of either one, two or three ordinates (saddle, cross-slide, table assembly, etc.). The play between slideways and their mating parts must be adjustable, particularly where wear is likely to occur and clearances have to be kept within prescribed limits. In most machine-tool slide and slideway arrangements, face to face sliding contact is usually found. If the mating faces are well produced and in good contact, specific bearing pressures are low, wear is small and load fluctuations are easily damped. The need of lightness in operation and for preventing "stick-slip" has sometimes led to the introduction of rolling devices (ball or roller bearings); *see* Fig. 1.27. Their application has, however, usually been limited to the execution of setting movements, where working loads due to cutting forces, etc. need not be considered and where the moving parts are rigidly clamped in position before the cutting operations are started.

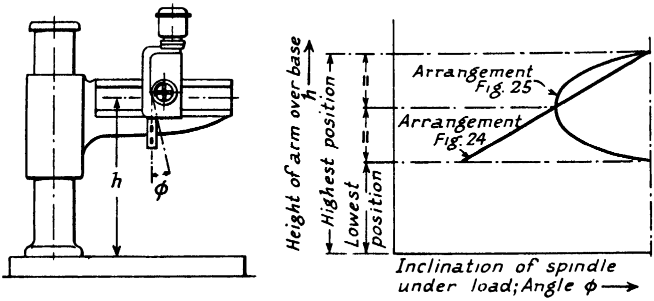

Fig. 1.26. Inclination of radial drilling machine spindle under load

Slides and slideways have to fulfil the following basic requirements: (*a*) Accurate alignment of the parts in question. This has to be maintained at any position of the moving parts and under working load. (*b*) Possibility of adjustment to facilitate, not only assembly, but also maintenance, especially compensation for wear. (*c*) Freedom from unnecessary restraint. (*d*) Possibility of efficient lubrication. (*e*) Prevention of swarf accumulation and ease of swarf removal.

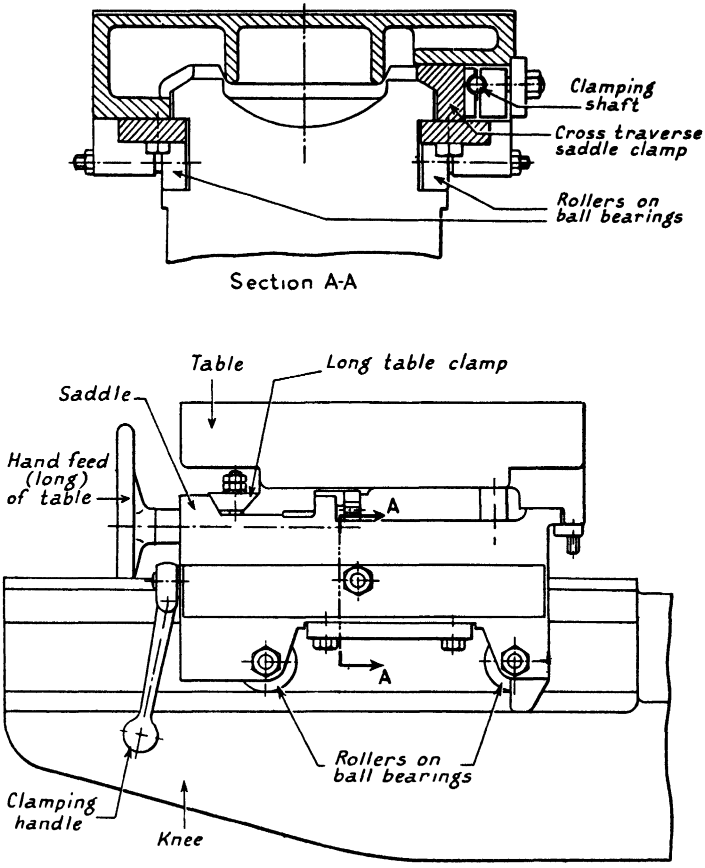

Fig. 1.27. Quick-acting table arrangement on vertical milling machine saddle on rollers

(*James Archdale & Co. Ltd., Worcester*)

The design of slides and slideways usually incorporates the following basic elements (Fig. 1.28) in various arrangements and combinations: (i) Vee-slide (Fig. 1.28*a*), (ii) Flat slide (Fig. 1.28*b*), (iii) Dove tail slide (Fig. 1.28*c*), (iv) Cylindrical slide (Fig. 1.28*d*).

The *Vee-slide* (Fig. 1.28*a*), arranged either upwards or downwards, gives location in two directions; that shown in the illustration gives vertical and horizontal location. To-day, most designers prefer a combination of one vee with a flat (Fig. 1.29*a*) because two vees (Fig. 1.29*b*) represent a statically over-determined guiding device and do not comply with requirement (*c*) mentioned above. It may be theoretically possible, although improbable in practice, to obtain perfect contact conditions on all four faces of two vees, but these conditions cannot be maintained when unequal wear takes place under the uneven load distribution that may occur.

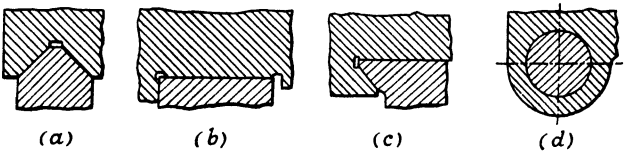

Fig. 1.28. Design elements for slideways

Vee-slide arrangements provide automatic play adjustment under the weight of the top part. The upward vee does not allow swarf to accumulate and is almost invariably used on lathe beds except in very large machines. The downward vee found in many large grinding and planing machines retains the lubricating oil, but the danger of a large accumulation of swarf can be overcome only by careful protection of the slideways (*see* Fig. 1.29*c*).

In centre lathes, two independent sets of slideways are used, one for headstock and tailstock which carry the workpiece, *a* in Fig. 1.30, and the other one for the saddle which carries the tool post, *b* in Fig. 1.30. This means that the wear of the saddle slideways, which is likely to be greater because of the almost continuous movement of the saddle under load, does not affect the accuracy of alignment of the fixed headstock nor that of the tailstock which is only occasionally moved and normally not under heavy load.

The *flat slide* arrangement (Fig. 1.31) is used extensively for heavy duty work and large and heavy machine tables. It separates the guiding actions in the vertical and horizontal directions and thus enables the fitter to align mating parts independently in the two planes. A narrow arrangement (short distance *a*) of the vertical guiding faces which give guidance in the horizontal plane, avoids the danger of jamming.

Adjustment of clearances is effected by strips which are either

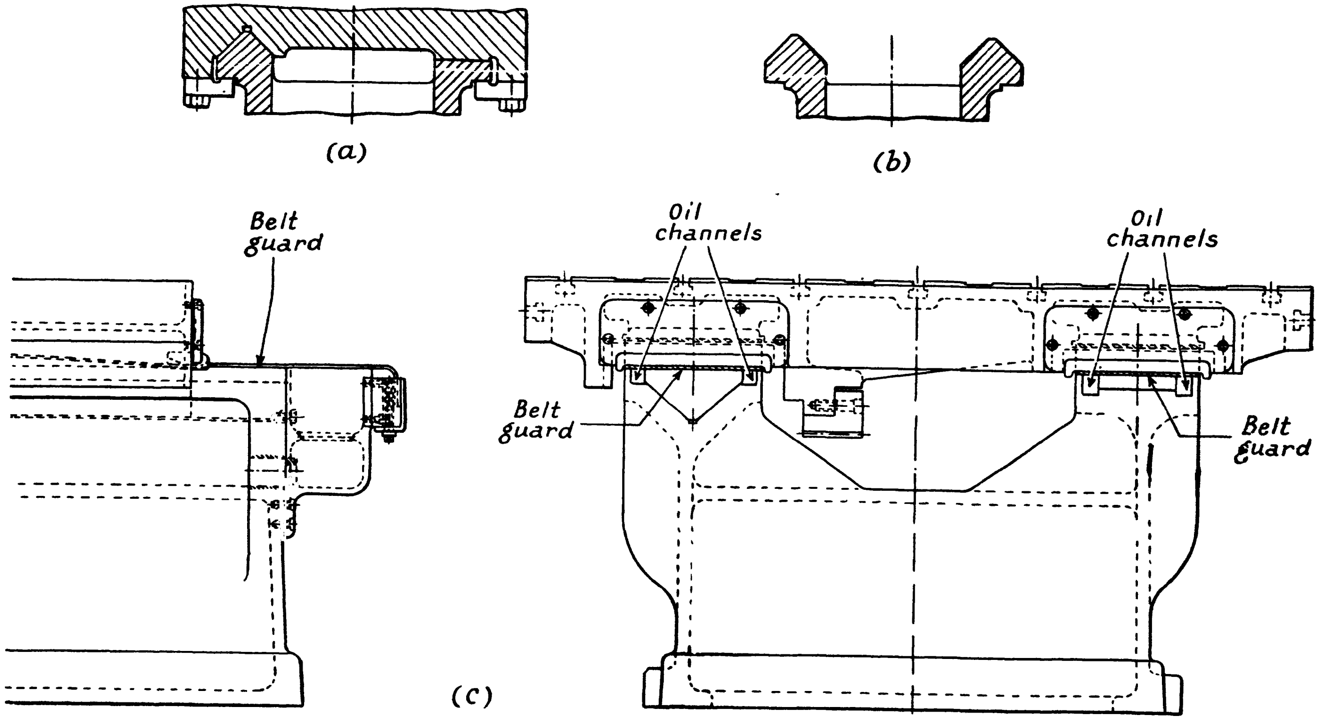

Fig. 1.29. Vee-slide arrangements. (*a*) Vee and flat. (*b*) Two vees. (*c*) Downward vee and flat slideways and slideway guards of a slideway grinding machine

(*Churchill Machine Tool Co. Ltd., Manchester*) parallel and set-screw controlled (Fig. 1.32*a*), or tapered and adjusted by axial movement (Fig. 1.32*b*). If not only directional but also positional adjustment is required, two strips (1 and 2 in Fig. 1.32*c*) may be necessary. If only one strip is used it is arranged on the side which is not normally subjected to heavy pressure.

Dovetail slideways (Fig. 1.33) are widely used for the guidance of parts producing feed movements such as lathe cross-slides or milling-machine tables, saddles and knees. The possibility of combining adjustment in two directions with a simple adjusting strip is often an advantage.

The detail design of the adjusting strip depends on the type of application. The simplest type is adjustable by means of set screws (*see* Fig. 1.32*a*) and is employed where working loads are likely to be small. A taper strip (*see* Fig. 1.32*b*) gives more uniform load distribution but difficulties may be encountered on dovetail slides when on long slides or slideways its thickness (taper 1 in 48 to 1 in 96) at the larger end becomes so great that the guiding device loses its stability. An arrangement using a strip with a dovetail angle of 45° on one side and an angle of 50° on the other (Fig. 1.34) has been used to overcome this difficulty.

When relatively small parts with dovetail slides have to be assembled, the fitter can slide them along the full length of the slideways into position. Conditions are not so easy when heavier parts, e.g. milling machine knees, etc., have to be handled. With these, the arrangement (Fig. 1.35) is often employed, where part a can be held in position at any point of the slideway b, and strip c can then be added to provide not only rigid guidance but also, through the tightening bolts d, adjustment for play. Care must be taken to see that the distance x and angle α are such as to make assembly or withdrawal possible, i.e. x must be greater than y.

A *cylindrical slide* arrangement makes the application of fully kinematic design principles possible; it requires, however, very accurate machining because adjustment or fitting by scraping is hardly possible. Very rigid guiding conditions can be obtained, and the design is used in the overarm design of some milling machines. Another typical application is of course found in the axially movable spindles of drilling and boring machines (Fig. 1.36).

(3) THE SPINDLE IN ITS BEARINGS has to hold the tool (drilling, boring, grinding, milling machines) or the workpiece (lathe) securely, and to guide them in their rotating movement with the accuracy required for the quality of production. For this purpose it has a

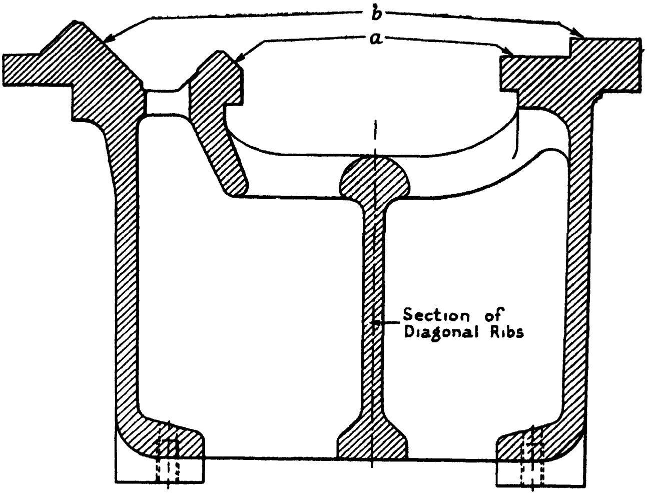

Fig. 1.30. Section through lathe bed
(*Dean, Smith & Grace Ltd., Keighley*)

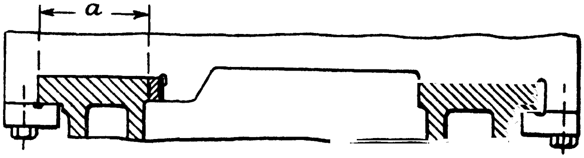

Fig. 1.31. Flat slide arrangement

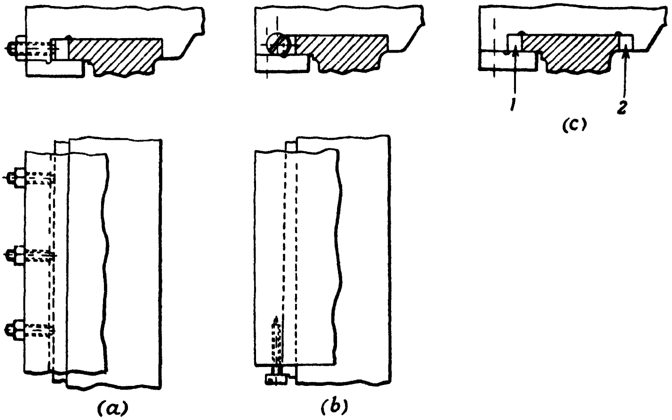

Fig. 1.32. Arrangements of adjusting strips

locating part, the spindle nose *a* and *b* in Fig. 1.37, or the internal taper *c*, and it runs in bearings which are designed—from the point of view of rotational movement—on principles similar to those mentioned under (*a*), (*b*), (*d*), page 30, in connection with slideways.

The external location device is either a cylinder or a taper. On lathe spindles a cylindrical portion, *a* in Fig. 1.37, acts as spigot for the concentric location of chucks, etc. As a screw thread will rarely, if ever, provide accurate concentric location, the screw thread *b* holding the chuck axially in position against the shoulder must be free and almost a loose fit so that it will not interfere with the locating action of the cylinder.

The usual device for internal location is the taper, which combines the possibility of assembling tightly and without play with that of easy disconnection by axial pressure or impact. The Morse taper (approx. ⅝ in./ft.) is sufficiently self-locking to hold the centred part in position, and it is even capable of transmitting (by friction) a torque, for instance the cutting torque of the drill. A bar, *d* in Fig. 1.37, inserted through the back of the hollow lathe spindle can be employed for knocking the taper out. The drilling machine spindle cannot normally be made hollow and its tail is often high and out of reach of the operator (*see* Fig. 1.36). For this reason one or two slots are provided through which a taper key can be inserted. This is used to impart an axial blow on the tongue at the end of the drill shank.

Frequently the load acting on a milling cutter is too great to be transmitted by friction in a Morse-type taper. Excessive torque or load may cause damage to the surface of the taper which cannot be dismantled with the ease required under such conditions. For this reason a special milling spindle taper was introduced in the 1920's (Fig. 1.38), and the tasks of locating the arbor and transmitting the torque were separated. A steep taper (3½in./ft.) which can be easily dismantled locates the arbor in the spindle, and two tenons *a*, held in position on the spindle nose by socket-head screws, serve for transmitting the torque. As the steep taper is not self-locking the arbor has to be held tightly in the spindle by means of a draw bar *b*. The double-sided axial location of the draw bar at the spindle tail facilitates dismantling, because by unscrewing the draw bar the taper is pushed out of its seating.

The running accuracy of the spindle depends to a great extent upon the design and quality of its *main bearings* which—similar to

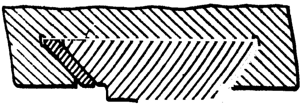

Fig. 1.33. Dovetail slideway

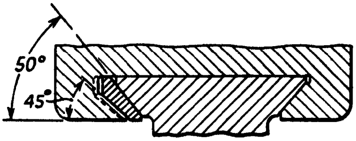

Fig. 1.34. Arrangement of taper strip for dovetail slideway

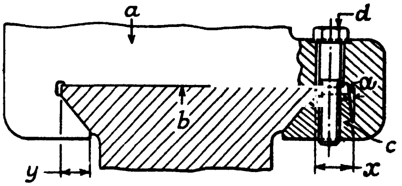

Fig. 1.35. Heavy duty adjustment strip arrangement

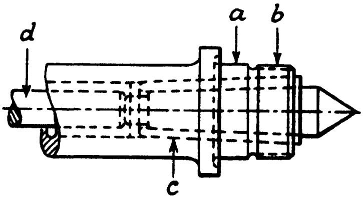

Fig. 1.37. Lathe spindle nose

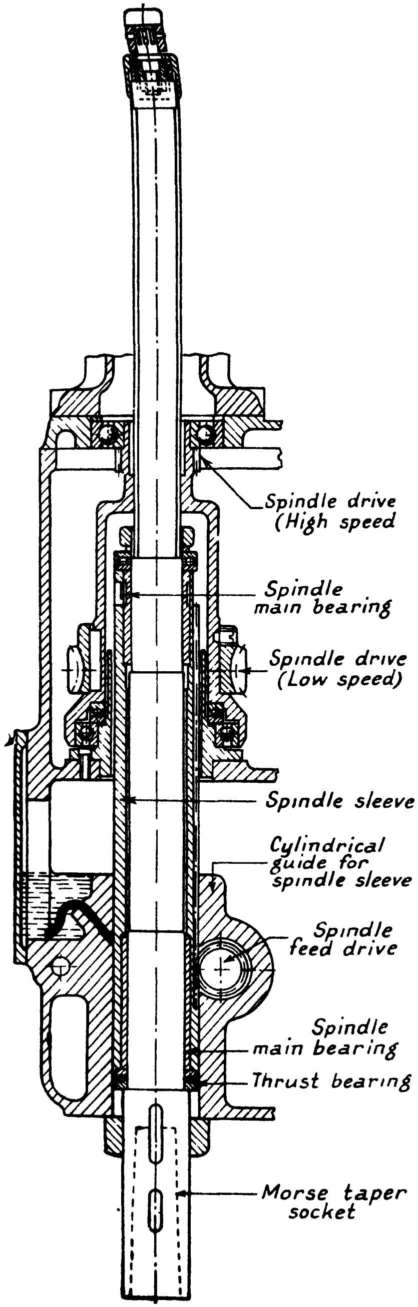

Fig. 1.36. Spindle of radial drilling machine

(*Wm. Asquith Ltd., Halifax*)

the conditions laid down for slides and slideways (*see* page 29)—must not only provide accuracy of concentric running but also maintain the same under load. Possibilities of compensation for wear are, of course, also essential where the maximum permissible deviations from ideal conditions are a few ten-thousandths of an inch.

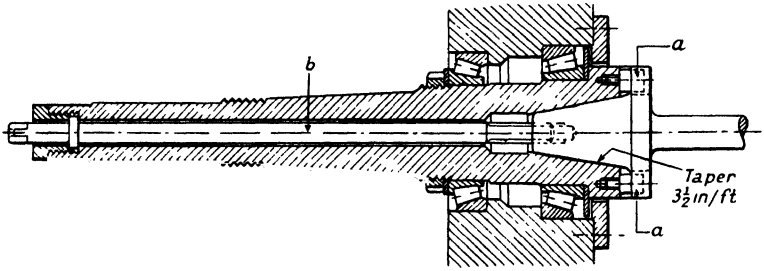

Fig. 1.38. Milling machine spindle and main bearings

Adjustable ball and roller bearing arrangements, such as angular contact ball bearings, ball bearings on tapered sleeves and taper roller bearings (*see* Fig. 1.38) are often found, but special arrangements of mounting and high quality bearings have to be used because irregularities, even in the position of the rolling parts, may create variations in the location of the spindle centre-line resulting in a certain degree of eccentric running. Smooth and steady running conditions are more easily achieved with plain bearings. However, their application is not completely free from difficulties because the speed and load range of a universal machine tool spindle may be very wide indeed. As an example, the spindle of a universal milling machine may run at 1,200 r.p.m. or more when light cuts are taken with a small end mill, while heavy cuts may be taken at a speed as low as 60 r.p.m. or even less. The load-carrying capacity of plain bearings that are not pressure lubricated grows, however, with the spindle speed, while in the example quoted, the highest load occurs at the lower speed. Furthermore, for highest efficiency, the clearances in the bearing ought to be adjusted to suit the speed and the load, and this may sometimes be difficult to reconcile with the requirement of minimum play which must be observed for reasons of accuracy.

Adjustment of play by means of tapered slotted bushes (Fig. 1.39) is still in use. Care has to be taken to prevent collapse of the bushes, which might cause the bearing to seize. Solid tapered bearings, adjustable by means of axial displacement in relation to the spindle (Fig. 1.40), are perhaps more difficult to manufacture, but they are easier to maintain and have a greater load-carrying capacity than slotted bushes.

Self-adjusting bearings have also proved very successful and the Cincinnati "Filmatic" bearing (Fig. 1.41) is a typical example.

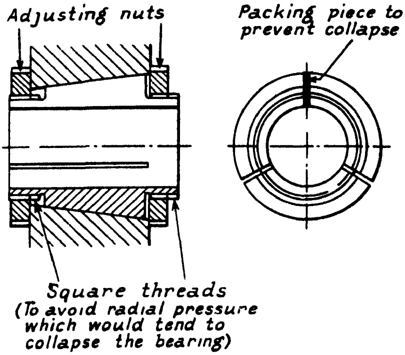
Adjusting nuts
Packing piece to prevent collapse
Square threads
(To avoid radial pressure which would tend to collapse the bearing)

Fig. 1.39. Adjustable split bearing

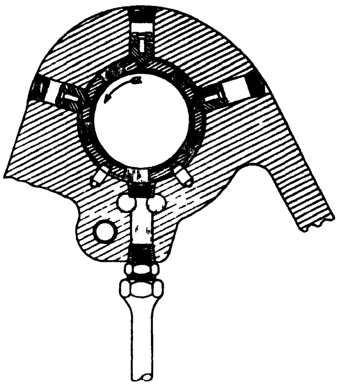

Fig. 1.41. Cincinnati "Filmatic" bearing

The spindle is surrounded by five longitudinal pads supported on studs and the whole assembly is immersed in oil at a slight pressure. As the spindle revolves it drags the oil round and forces it into the leading edges of the pads, which tilt and grip the spindle.

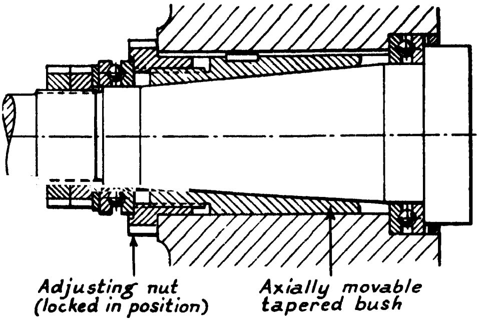

Fig. 1.40. Tapered bearing bush
(axial adjustment)

As far as loading conditions on spindles and bearings are concerned much can be achieved by consideration in setting up the machines. An example is the use of a single or double-headed carrier on a component turned between centres (Fig. 1.42). The load on the headstock centre and through it on the main bearing varies in magnitude and direction periodically during each rotation if a single-headed carrier is used (Fig. 1.42*a*), while it remains steady and in the same direction when a double-headed carrier is employed

(Fig. 1.42*b*), because no reaction of the tangential driving force $P_1 = T/r$ has to be taken by the centre itself, the torque being taken by the two equal and opposite forces $P_2 = T/2r = P_1/2$.

The efficiency of machine tools depends greatly upon the lubrication of bearings, slides and slideways, control gears, etc. While the problem of design, choice of bearing materials and surface finish of the sliding faces is a matter for the machine tool designer and manufacturer, the user, that is, the engineer in industry, must look after the actual lubrication of his machine tools in service. He must see to it that the recommended suitable lubricants are applied whenever and wherever necessary. Many machine-tool makers issue lubrication instructions (Fig. 1.43), and some provide centralized lubrication points from which, with a single operation of a lever or piston, a number of bearings, etc. are lubricated simultaneously.

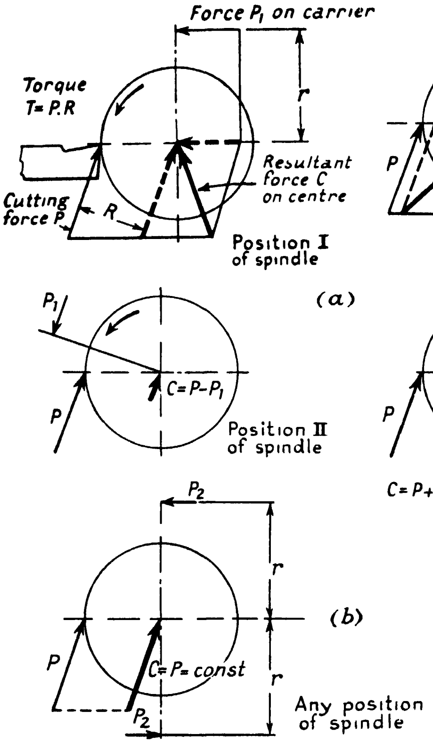

Fig. 1.42. Effect of the carrier arrangement for lathe turning upon the loading of the main bearing

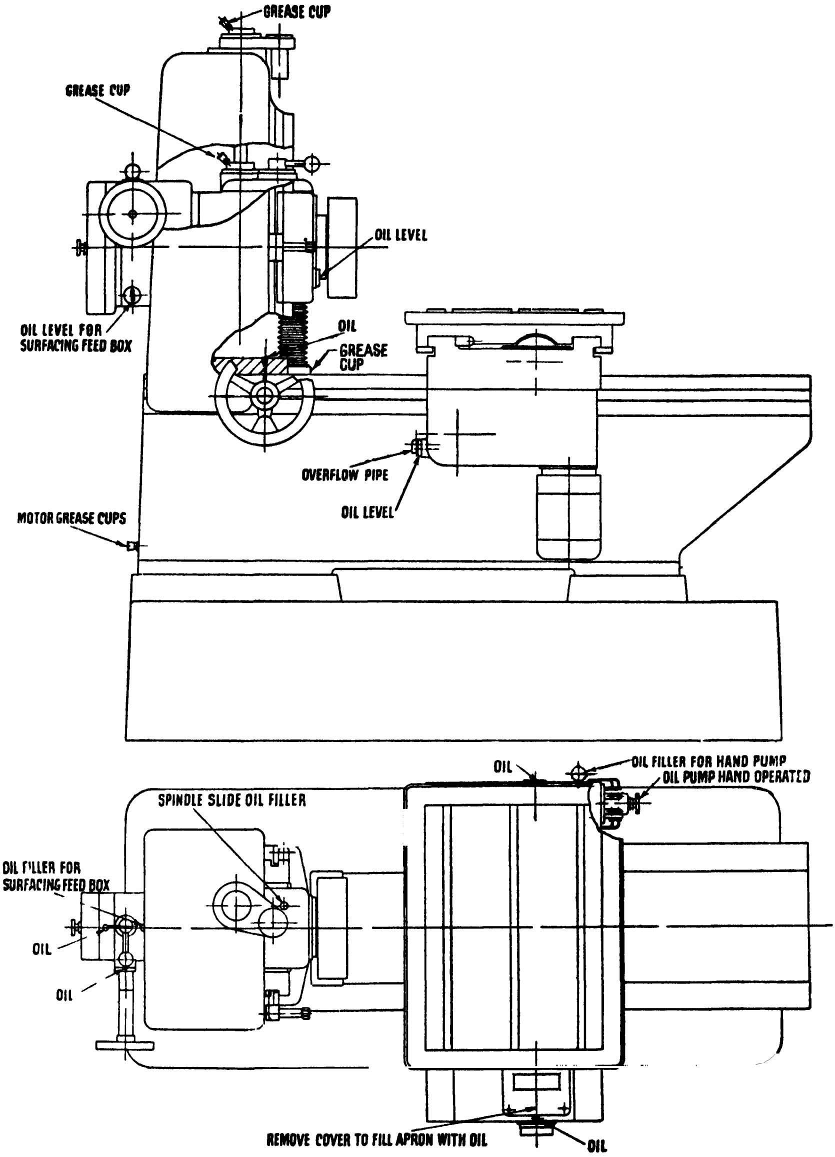

Fig. 1.43. Lubrication instruction for horizontal borer

(H. W. Kearns & Co. Ltd., Broadheath, Manchester)

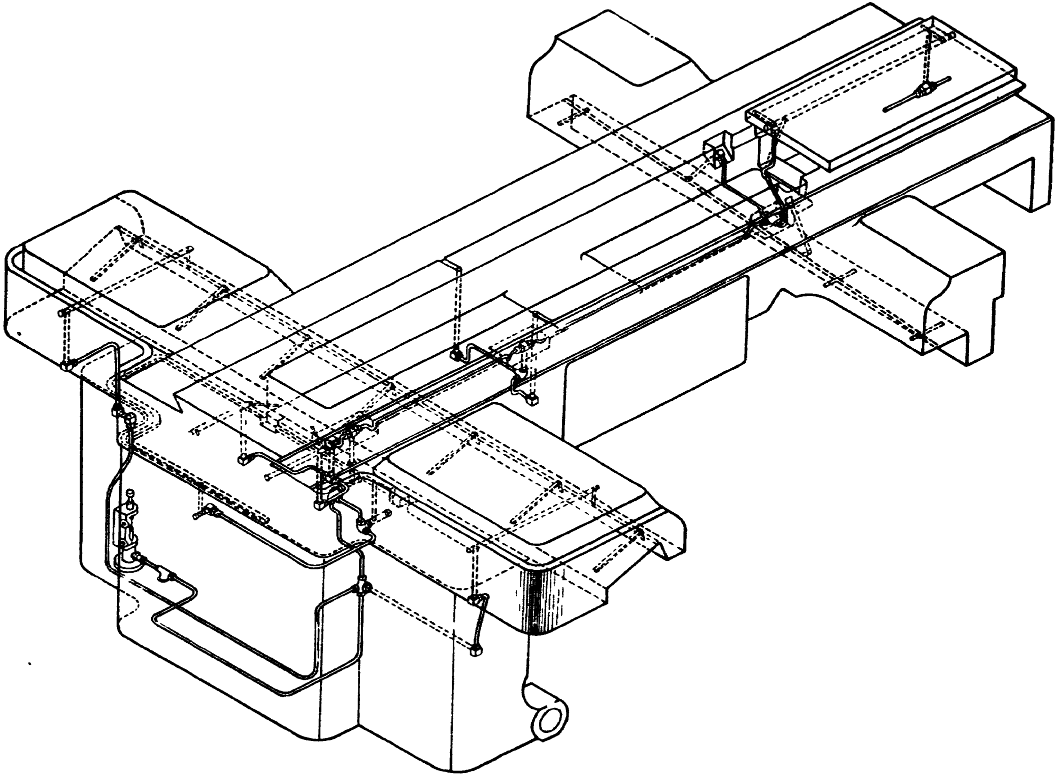

Fig. 1.44. Automatic lubrication system for saddle and apron of a large lathe

Completely automatic lubrication arrangements not only eliminate the danger of a careless operator neglecting his duties in this respect, but also allow the conscientious machine operator to concentrate on the essential work of getting satisfactory output from his machine. In the system (Fig. 1.44)* for lubricating the saddle and apron of a large lathe, a cam-operated piston-type pump, driven by the feed drive in the apron, supplies the oil and distributes it to gears and bearings in the apron and to slides and slideways of the saddle on the bed, the cross slide on the saddle and the tool slide on the cross slide.

(4) Operating, Setting and Control Devices. The output of a machine tool in the production shop can be greatly reduced if setting and handling times are excessive and if accidental or faulty operation is not prevented. The arrangement of levers, crank handles, etc. within easy reach of the operator, possibly duplication to suit different positions from which operation might be required, and the provision of push-button control boxes (sometimes suspended on a jib-type arm) for remote control, help in reducing operating times.

The effort required for operating the levers, hand-wheels, etc. can be kept low by providing suitable gear reductions or by ensuring conditions of low friction (roller slides, recirculating ball nuts, etc.). When the movement required for the turning of crank handles or hand-wheels is also used for measuring the displacements of the moving parts, high mechanical reduction may cause excessive setting errors (e.g. due to the play in reduction gears or the pitch error of screws, especially when a certain amount of wear has taken place). In precision machines the functions of operating (moving) and measuring are, therefore, often separated. For example, it will be found that in most modern jig-boring machines mechanical or hydraulic drives for setting operations are used in conjunction with optical devices for precision measurement.

Damage can be caused by the operator moving a handle, lever or hand-wheel: (*a*) in the wrong direction, thus initiating a movement in a direction opposite to the one required; (*b*) when it should not be moved at all, i.e. when the operation thus initiated on the machine would interfere with other operations in progress.

The directional control of machine movements and the correlation between operating devices and moving machine-tool parts has been standardized on the following general principles by BS. 754:

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* Whalen, W. D.: "Modern Machine Tool Lubrication Practice", *Mechanical Engineering*, Oct. 1952.

1937: British Standard System *for the Direction of Rotation of* Machine Tool Hand-wheels and Levers relative to Movement produced:

> "The direction of rotation of (operating) cranks, hand-wheels and levers, etc. shall be judged from the operating position, or as seen from the outside of the machine looking in the direction of the axis of the operated member.
>
> For screw-operated machine members, clockwise rotation of the crank or hand-wheel in general moves the machine member affected towards the cutting position.
>
> In rack and pinion mechanisms or the equivalent where the crank or hand-wheel moves in a plane parallel to the movement produced, the general rule is that the part of the crank or hand-wheel which will normally be gripped by the operator moves in the same direction as the member of the machine affected."

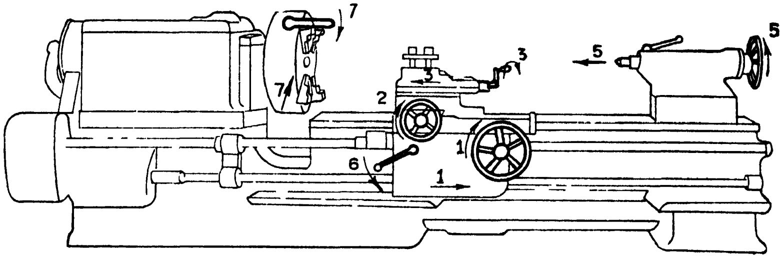
An example of the application of these principles is shown in Fig. 1.45. This is from B.S. 754: 1937.

Such a standardization ensures an arrangement which might be called logical, because movements produced are in accordance with the result which the operator would reasonably expect from his action. Furthermore, the fact that these directions of movement and rotation are standardized at all ensures that an operator need not change his accustomed actions when he has to move from one machine to another.

The danger of initiating a faulty operation is normally prevented by interlocks which may be electrical, mechanical or both. If the feed drive of a milling machine table is derived from that of the milling spindle, mechanical feed movement is possible only if the milling cutter is rotating, and no damage can be done. If the milling spindle and table feed are driven by separate electric motors, an electrical interlock can prevent the operator from starting the table feed before he has started the milling spindle. With the lathe, simultaneous engagement of the longitudinal feed operated by rack and pinion and of that operated by the lead screw would result in some breakage, and a simple mechanical interlock is usually provided to help prevent such damage.

Testing Alignments and Performance. Machine tools for the modern workshop must be able to produce workpieces of a given accuracy, within prescribed limits, consistently and without requiring high artistic skill on the part of the operator. The quality of the workpieces depends on: (*a*) the stiffness and rigidity of the machine tool and its component parts, (*b*) the alignment of the various parts of the machine in relation to one another, which must be maintained under load, (*c*) the quality and accuracy of the control devices and driving mechanisms.

Stiffness and rigidity are a matter for the designer and, once tests on the prototype of a certain design have given satisfactory results, there is no need to test machines of the same design over and over again.



Movable Part		*Operating Device*	
Description	*Movement*	*Description*	*Movement*
1. Carriage	To right	Handwheel or Crank lever	Top part moves to right
2. Cross slide	Setting the tool for outside turning		Clockwise
3. Swivel slide	Towards chuck		,,
5. Back centre	,,	Handwheel	,,
6. Nut for lead screw	Engaging of nut	Lever	Downwards
7. Chuck jaws	Towards centre	Box spanner	Clockwise

Fig. 1.45 Direction of rotation of lathe handwheels and levers (from British Standard 754 : 1937)

The accuracy of manufacture, the precision of control devices and driving mechanisms, the relative alignment of the various parts of the machine and the play which may affect this alignment under loading conditions depend, however, on the quality of manufacture and may vary from one machine to another. It is advisable, therefore, to subject each new machine to an acceptance test concerning the items (*b*) and (*c*) above before it is installed.

If a machine tool were required to produce only one single type and size of workpiece, its accuracy and performance could be easily tested by measuring a number of such workpieces as they come off the machine. A universal machine, however, may be required to produce a wide range of types, shapes and sizes of components. It may therefore have to operate under conditions of almost unlimited variety as regards relative positions between its parts, and an acceptance test consisting of the examination of all typical pieces which can be produced on the machine would be impossible. For this reason the following procedure is generally adopted:

(*a*) The *relative alignment* of all parts of the machine and the accuracy of the control devices and driving mechanisms (such as the lead screw of a lathe) are measured under no-load conditions. The results of these measurements must lie between prescribed limits.

(*b*) The *driving mechanisms* are tested over their full range by measuring output speeds, observing irregularities caused at particular settings, etc.

(*c*) Typical *test pieces* involving the use of various types of finishing operation (in the lathe, cylindrical turning between centres, and in a chuck, surfacing, etc.) are produced on the machine and measured to determine whether or not the alignments found under no-load conditions are maintained under load, and how the machine behaves generally under working conditions.

It is, of course, necessary to distinguish between performance of output (rate of metal removal) and performance of accuracy. The former applies to roughing, the latter to finishing operations only. So long as the machine parts are not overstressed and do not suffer permanent deformations, the magnitude of these deformations is of little importance during roughing operations, because accurate components are expected only from finishing operations. Often, machines will be intended for carrying out either one or the other, not both, but even with universal machine tools it is essential to remember that for tests concerning accuracy, only finishing operations need be considered because the deformations during roughing operations are bound to be beyond those given in the precision test specifications.

A specification for the alignment tests must comply with the following general requirements:

(*a*) The procedure for testing standard machine tools must not require more than about six to eight hours' work, provided all the necessary tooling and measuring equipment is readily available.

(*b*) The permissible limits of accuracy of individual measurements must be wide enough to make economical manufacture possible, while on the other hand the cumulative error of a number of superimposed details must not become excessive.

Detailed instructions and specifications of acceptance tests have been published* and are in general use.

The principles and methods of these tests may be explained from the Schlesinger test chart shown in Fig. 1.46, where a centre lathe is used as an example.

Before the actual acceptance test is started the machine tool must be carefully levelled, usually by means of a precision spirit level. Fig. 1.46*a* shows the levels (positions *a* and *b* of the spirit level) which have to be checked over the full-length of the bed. In general the front slideway *a* is allowed to be convex only, because the cutting torque exerted on the bed will normally tend to press this slideway downwards. To avoid too large a cumulative error resulting in excessive twist, a check *c*, again at different positions over the length of the bed, serves for keeping the twist within permissible limits.

This operation is not an acceptance test only, in the usual sense of the word. The operator does not merely measure the shape of the bed whatever it may be. He may have to twist the bed on its foundation—by means of wedges and foundation bolts—until it is as near as possible to its correct shape. To succeed in doing so is , of course, possible only if the bed had been manufactured correctly in the first place. In machines above a certain length (10 feet) the straightness of the slideways in the horizontal plane may have to be checked by a microscope fixed to the saddle and travelling along a tight wire (Fig. 1.46*b*). Deviation from straightness of the saddle slideways would result in a variation in diameter over the length of an (intended) cylindrical workpiece.

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* Schlesinger, G.: *Testing Machine Tools*, 5th edn., Machinery Publishing Co., 1954. (First published in German, 1927.)

Salmon, P.: *Machines-Outils, Réception-Vérification*, first published 1937.

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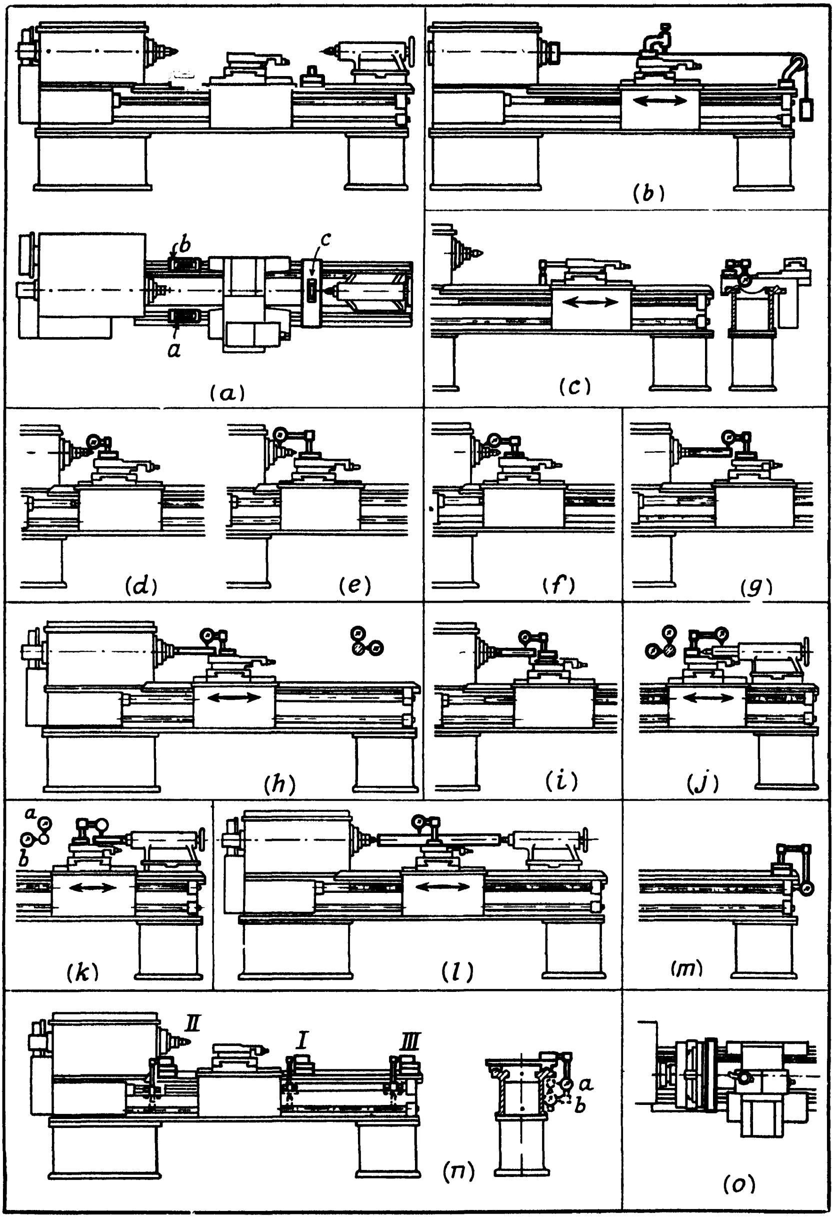

Fig. 1.46. Schlesinger test chart for centre lathes

The parallelism between the tail stock slideways and the saddle slideways is next checked by means of a clock gauge which is clamped to the saddle and travels with it along the bed (Fig. 1.46*c*). This test is best carried out in two positions of the clock gauge, i.e. on each flank of the Vee. Errors in this parallelism would result in tapered workpieces, the amount of taper depending on the tailstock position on the bed.

The next tests concern the main spindle which is examined for:

1. *True running* (roundness, angularity and concentricity) of (*a*) the centre (Fig. 1.46*d*); (*b*) the internal taper (Fig. 1.46*g*); (*c*) the external locating cylinder or taper (Fig. 1.46*e*).
2. *Axial float* (Fig. 1.46*f*).

The true running of the internal taper is usually measured (by means of a clock gauge) at the end of a 12 in. long test mandrel which

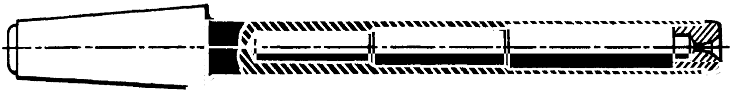

Fig. 1.47. Test mandrel

is inserted in the taper. Test mandrels (*see also* the one used for test, Fig. 1.46*l*) have to be prepared with great care. While the dimensional accuracy of the mandrel diameter itself is of relatively little importance, the accuracy of true roundness and cylindricity as well as that of concentricity between the tapered and the cylindrical portion has to be of the highest order. Sagging of the mandrel under its own weight may cause measuring errors, and to reduce their weight such test mandrels are usually made hollow (Fig. 1.47).

Errors mentioned under (1) cause eccentricity between machined surfaces and centres or cylindrical faces clamped in the chuck.

Axial *float* of the spindle must be clearly distinguished from axial *play*. Axial play is a normal feature of a thrust bearing and has no effect on true axial running as long as the thrust load is applied consistently in one direction. Axial float is due to lack of alignment of the thrust washers or shoulders and causes—even under axial load in one direction only—an undesirable axial oscillating movement of the spindle during its rotation. Test (Fig. 1.46*f*) is carried out for checking axial float, not axial play. Plane surfaces and shoulders cannot be obtained with facing operations if the spindle floats axially.

The running accuracy of the spindle (tests Fig. 1.46*d* to *g*) must be tested only after the spindle has been running for some time, to ensure that the bearings are at their normal running temperature.

The parallelism between spindle axis and saddle slideways is checked in both the vertical and horizontal plane (Fig. 1.46*h*). The spindle has to be turned into its mean position (mean reading of the clock gauge during one turn of the spindle), and the clock gauge on the saddle is then moved along the test mandrel by traversing the saddle along the bed. The mandrel must rise (within the permissible limits) towards the tailstock end of the bed and point towards the tool post, to ensure that the weight of the workpiece and the cutting force do not push the spindle away from, but rather towards, the zero position. Errors in parallelism between spindle axis and saddle slideways result in unintentionally-tapered workpieces.

The alignment of the tool rest (Fig. 1.46*i*) need be tested in the vertical plane only, because the tool rest is usually supported by a swivelling base. This test is carried out to ensure constant height of the tool during setting.

Tests similar to those mentioned for the spindle are carried out for the tailstock sleeve and internal taper (Fig. 1.46*j* and *k*), and the correct height alignment between headstock and tailstock is checked (Fig. 1.46*l*) by means of a 3 ft. long cylindrical, usually hollow test bar. The tailstock and the tailstock-sleeve must be clamped in position during the tests, that is, they are tested under their normal working conditions. For the reasons explained before, the permissible tolerance allows the tailstock centre, which may in time be lowered due to wear of the tailstock sliding faces, to be above and *never* below the headstock centre.

To ensure minimum pitch errors during screw cutting the lead screw is tested for axial float (Fig. 1.46*m*), and, for smooth feed movements, its parallelism with the saddle slideways on the bed is checked (Fig. 1.46*n*).

A simple method for determining the pitch error of the lead screw consists in accurately measuring the travel of the saddle for a certain number of turns of the lead screw (Fig. 1.48). A certain gear ratio between spindle and lead screw is set by means of the change wheels or the feed gear box. The initial position of the saddle is determined with a clock gauge *a* in Fig. 1.48*a* and a gauge block *b* which rests against a stop *c* rigidly fixed to the bed. The initial position of the spindle is determined by means of a clock gauge *d* set on the bed against the driver *e*. After removing gauge block *b* and clock gauge *d* the spindle is given a number of turns which should theoretically result in a saddle travel equal to the length of gauge block *b*. The exact completion of the last full turn of the spindle is checked with clock gauge *d* again measuring against driver *e* and the error in travel can then be read directly from clock gauge *a* which now measures against the face of stop *c* (Fig. 1.48*b*).

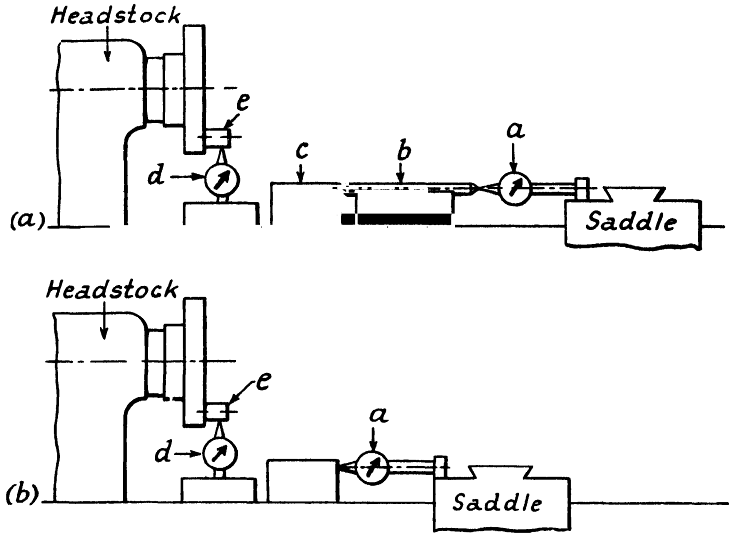

Fig. 1.48. Determination of the pitch error of a leadscrew

The squareness of the cross-slide movement with the spindle axis is deduced from an examination for flatness of a face produced by a finishing surfacing operation on the machine itself (Fig. 1.46*o*). Only concavity of the surface is allowed, because concave faces can be located accurately (Fig. 1.49*b*) while convex faces would tend to rock (Fig. 1.49*a*). The measurement of the machined face must of course be made independently of the lathe, and is best carried out by comparing the flatness of the surface under examination with a straight edge.

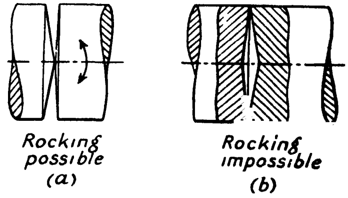

Fig. 1.49

After the tests for accuracy have been concluded, a final check of the general performance is provided by the following questions*:

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* From Schlesinger, G.: *Accuracy in Machine Tools, How to Measure and Maintain it*, and *Testing Machine Tools.*

1. Did the machine run satisfactorily at all speeds ?
2. Do all horizontal and vertical feeds work correctly ?
3. Do the gears run without noise ?
4. Is the machine free from vibration during the cutting operation ?
5. Has the lubrication equipment been inspected and is it in good condition ?
6. Are the bearings well adjusted? Do the carriage guides work without blacklash, and is the function of rotating and oscillating movements correct and uniform ?
7. Do the safety clutches or other safety devices function correctly ?
8. Are the dial rings and fine adjustments by hand correctly divided and marked ?
9. Is there any objection regarding the operation of the machine?

For Bibliography see end of book.

CHAPTER II

THE THEORY OF CUTTING TOOLS

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Introduction. A fundamental knowledge of the process of cutting is of considerable assistance in the rational design and use of cutting tools. The subject is complex owing to the many variables involved, and because there is yet no basic theory of cutting action which gives, for example, a relation between the rate of tool wear and the cutting conditions in terms of known factors. The present chapter attempts to correlate some of the more important results derived from experimental research, and it is hoped that it will provide a background for further reading. The mechanism of the cutting action of the simple wedge tool and the single-point tool will be considered in detail, along with the effects of the cutting conditions (e.g. cutting speed, depth of cut, etc.) on the roughness of the cut surfaces, the rate of tool wear and the cutting forces. By applying these general principles and taking into account the geometry of the individual operations, the reader will be able to understand the cutting action of the practical edge tools.

The Simple Wedge Tool. It is desirable to consider first the simplest type of cutting operation, in which the cutting edge is straight, parallel to the original plane surface of the workpiece, and perpendicular to the direction of cutting, and in which the length of the cutting edge is greater than the width of the chip removed. Such an operation has been described as *orthogonal* cutting (Fig. 2.1). The wedge forms the basic element of all cutting tools, where α is termed the rake angle, β the wedge angle, and γ the clearance angle. The wedge angle may be either acute or obtuse. The rake angle is defined as positive if $\beta + \gamma < 90°$, and negative if $\beta + \gamma > 90°$. It has an important influence upon chip formation and affects the type of chip, the cutting force, tool wear, and the roughness of the finished surface. The clearance angle has little effect upon chip formation, but it has an important effect on the rate of wear of the tool; this will be discussed later.

The number of direct applications of orthogonal cutting to practical cutting tools is limited. In general, the basic forms of most practical tools require three dimensions for their geometric definition. A second basic cutting operation is thus considered; this is the *oblique cutting operation* in which the cutting edge is again straight and parallel with the original surface of the workpiece, but is not perpendicular to the cutting direction, being inclined to it. The inclination of the cutting edge to a line normal to the cutting direction is known as the angle of obliquity; the rake and clearance angles of the tool are best measured, as in orthogonal cutting, in a

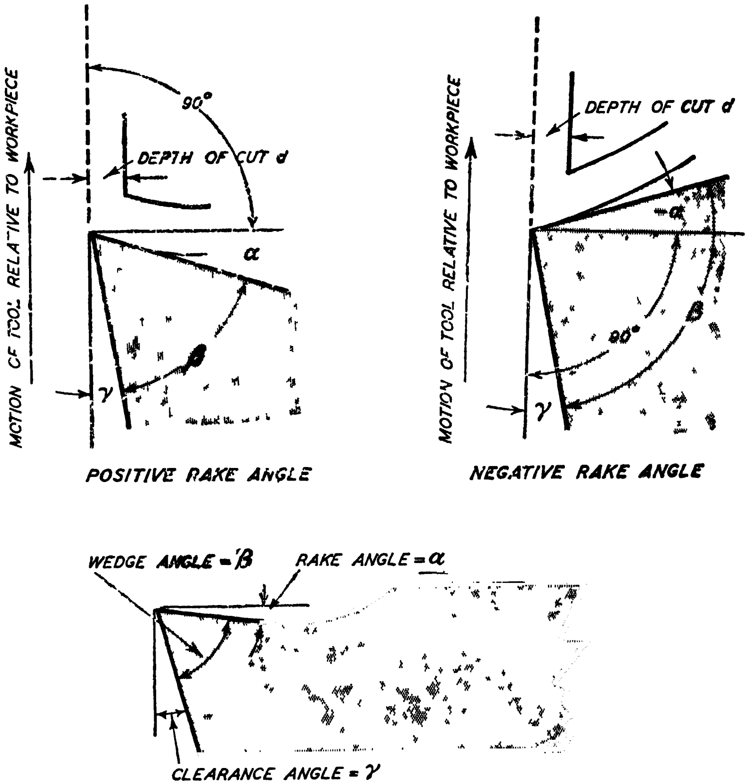

Fig. 2.1. Geometry of orthogonal cutting

plane normal to the cutting edge. In the earlier pages of this chapter the characteristics of the cutting process will be considered mainly in relation to the orthogonal operation.

Chip Formation

CHIP TYPES. The metallographic technique for examining the crystalline grain structure of a metal by polishing and etching has been found particularly useful in studying the precise manner in which a chip is removed from the workpiece, and the extent and nature of the plastic flow of the material in the region of the separation. The process consists of cutting a chip under known conditions and stopping the cutting action quickly, so that the chip and the workpiece are left in a condition close to that existing during the actual cutting operation. The portion of the workpiece with the chip adhering is cut out, and is electroplated with a thick coating of copper or nickel in order to preserve the edges of the specimen and to prevent damage during the subsequent operations. The plated specimen is then sectioned in a plane parallel to the direction of cutting and perpendicular to the generated surface; it is polished and etched by the usual methods, and is then examined under a microscope.

A number of devices has been built for decelerating the moving parts fast enough to ensure that the specimen obtained is representative of the conditions at the cutting speed under investigation. One such device has been used to study the mechanism of chip formation in the grinding process.

Mallock in 1881 studied the process of chip formation for a variety of materials, examining, among other things, the effect of a "lubricant" (water) used when cutting soap. Rosenhain and Sturney,* using the metallographic technique described above, examined the chip formation when cutting mild steel and brass under orthogonal conditions at the comparatively low speed of 4 ft./min. They defined qualitatively three types of chip which they termed the *tear*, *shear* and *flow types*. They pointed out, however, that these terms were not fully descriptive of the process by which each type of chip was formed.

Fig. 2.2*a* shows an example of a *tear type* chip. Severe distortion of the metal adjacent to the tool face occurs and ultimately results in a crack running ahead of the tool. This crack separates the zone of distorted metal from that of the relatively undistorted body of the workpiece and, in general, runs slightly inwards and away from the direction of cutting. Eventually the shear stress across the chip becomes equal to the shear strength of the material, and fracture and separation of the chip occur. With this type of cutting there is little relative movement of the chip along the tool face, and as a result of the crack, the tool removes metal to a greater depth than is intended.

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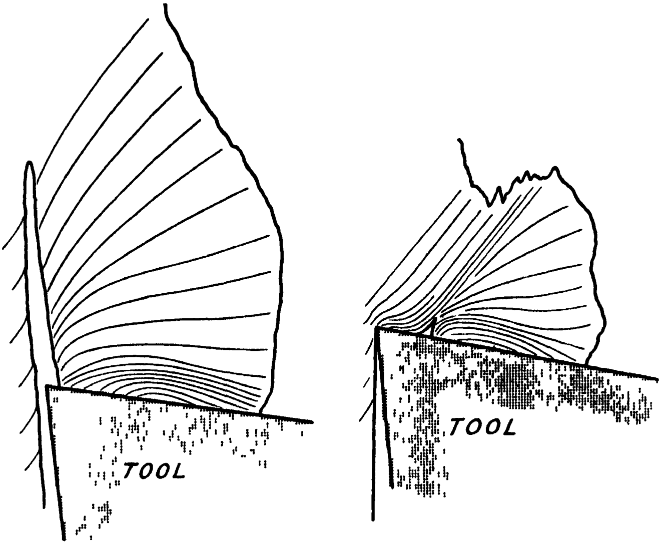
* *Proc. Inst. Mech. Eng.* (1925), 2, 141.



(a) Tear-type (b) Shear-type

Fig. 2.2. Discontinuous chips. Flow lines indicate direction of maximum elongation

In the *shear type* chip (Fig. 2.2*b*) the tearing action gives place to a general motion of the chip along the tool face, but the nature of the cutting is again intermittent. The plastic deformation of the metal takes place in a manner similar to that occurring in the tear type chip, with the greatest distortion adjacent to the tool face. The crack preceding the tool does not in this case extend so far, and complete fracture of the chip does not necessarily take place. As the relative motion between the tool and the workpiece proceeds, the shear stress reaches a value at which severe local plastic slip occurs, and a segment of the chip is displaced and moves along the tool face.

Continuous cutting takes place with the *flow type* chip (Fig. 2.3) which also shows the existence of a localized highly deformed zone of material seated on the tool face and which seems to take part in the cutting action. Rosenhain and Sturney assumed that this deformed zone was the structure which had for some time been known as the *built-up edge*, and whose appearance on the tool point after a cutting operation was familiar to machine operators as "build up".

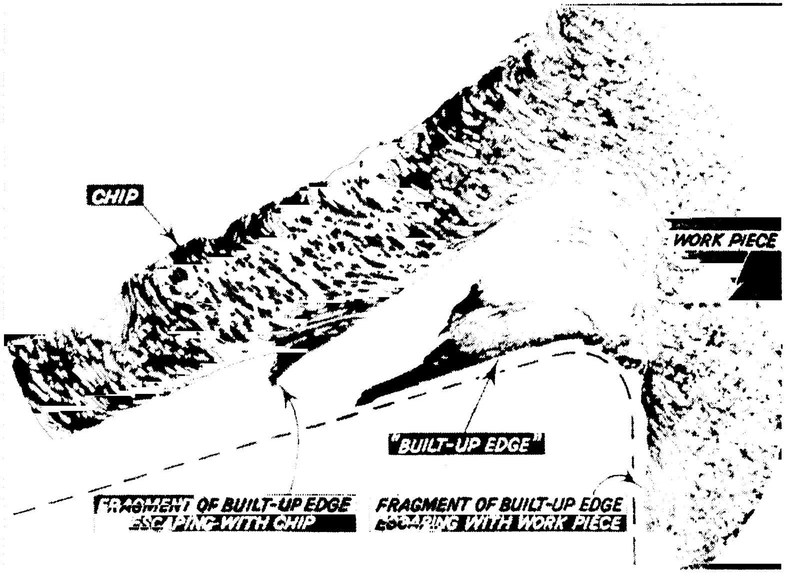


Fig. 2.3. Photomicrograph showing flow-type chip with built-up edge
Depth of cut = 0 020 in. *Cutting speed* = 83 ft./min.
(*Ernst & Martellotti*)

The model illustrated in Fig. 2.4 demonstrates how a *continuous* or *flow* chip with no built-up edge could be formed by simple shear along a *shear plane* extending from the cutting edge to the original surface of the workpiece. Although the chip is shown in the figure as a stack of cards, it is important to appreciate that the severe plastic deformation of the chip material is not in practice normally accompanied by fracture. Examination of photomicrographs of actual chips shows that chips of this type could be formed approximately by the type of deformation illustrated in the model. In other cases, however, the outer surface of the chip and the original work surface are joined by a pronounced curve. The inclination of the plane of shear to the cutting directions (and the shear angle φ) is affected in practice by the

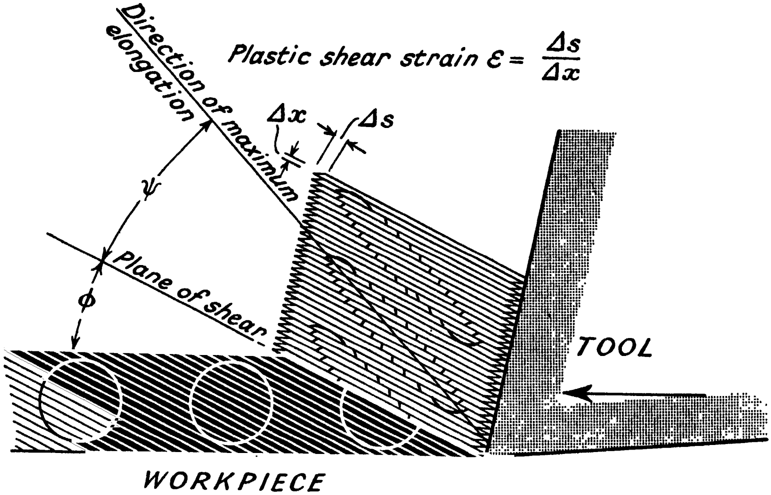

Direction of maximum elongation
Plastic shear strain $\varepsilon = \frac{\Delta s}{\Delta x}$
Δx
Δs
ψ
Plane of shear
ϕ
TOOL
WORKPIECE

Fig. 2.4. Model demonstrating shear deformation in continuous chip with no built-up edge

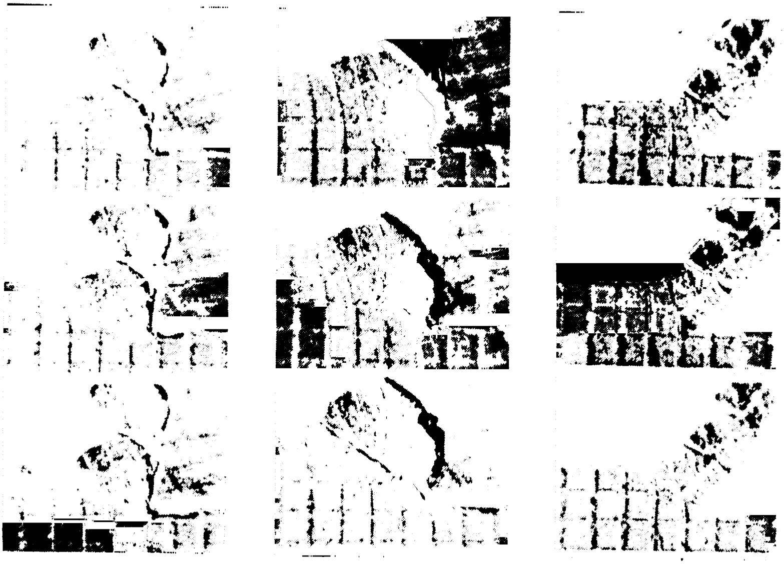


Fig. 2.5. Shear-type chip formation cutting a high lead bronze

Cutting speed = 1 in./min.

$d = \frac{1}{16}$ in.
$\alpha = 10°$

$d = \frac{7}{64}$ in.
$\alpha = 10°$

$d = \frac{1}{16}$ in.
$\alpha = 35°$

(Ernst & Martellotti)

properties of the work material and by the cutting conditions; it affects the amount of plastic strain and hence the energy required for cutting. A number of attempts has been made to predict theoretically the shear angle, and these will be discussed later.

In general, a brittle material such as hard brass tends to form a *shear type* or *discontinuous* chip (Fig. 2.5), whilst a ductile material, such as mild steel, forms a continuous or flow type chip. An increase in the rake angle, or cutting speed, or lubrication of the chip on the tool face, gives rise to a greater tendency towards the flow type chip, whilst an increase in the depth of cut causes a greater tendency towards the shear type, and ultimately towards the tear type chip.

THE BUILT-UP EDGE formed at the tool point is of interest because of its effect upon the nature of the cut surface and upon tool wear; it is therefore valuable to make a more detailed study of its structure and the factors which influence its formation.

Fig. 2.3 shows a cross-section of a built-up edge formed when cutting nickel-chromium steel. The tool, in moving relative to the workpiece, elongates the material at the underside of the chip and at the surface of the workpiece in the direction of cutting. Where the under surface of the chip and the new surface of the workpiece are formed, the elongation of the material is approximately at right angles to the direction of cutting. It seems that under certain force and temperature conditions this material tends to build up on the rake face and starts the formation of a built-up edge. As the cutting proceeds, the material at the junction of the chip and the workpiece is laid over the dome of the built-up edge, and is strained and work-hardened until fracture of the material occurs on each side of the structure. Thus the new surfaces are formed. The elongated and work-hardened material between the two fractures remains at the tool point and tends to pile up continually.

Rosenhain and Sturney have confirmed the above conceptions by showing that the built-up edge is continuous with the body of the chip and the workpiece. Fig. 2.6*a* shows a built-up edge obtained when cutting brass, and Fig. 2.6*b* shows the same one after the specimen has been heated above the recrystallization temperature. It will be seen that the strained crystal grains have regained their normal state. When a material has cooled after being heated above its recrystallization temperature, the disposition of the new crystal grains shows up such discontinuities in the material as cracks and welds. The built-up edge is therefore continuous with the surrounding material of the chip and workpiece. Prior to these experiments it was thought that the built-up edge consisted of particles of material scraped from the workpiece and welded together under the influence of the high temperatures and pressure existing at the tool point.

Schwerd* has explained that as the cutting proceeds the built-up edge grows in size and its dome moves in towards the workpiece; eventually a portion of the structure appreciably overhangs the tool point and, at some stage, fracture of the built-up edge occurs and a fragment of the built-up edge then moves away as part of the surface of the workpiece. A similar fracture occurs on the upper side of the built-up edge, so that fragments are also carried away by the under surface of the chip (Fig. 2.7). To give an idea of the frequency of deposition, examination of a number of surfaces has shown that the fragments are deposited at intervals of the order of 0·001 in. to 0·010 in. apart. At a cutting speed of 10 ft./min. the frequency of deposition would therefore be about 2000 per second to 200 per second.

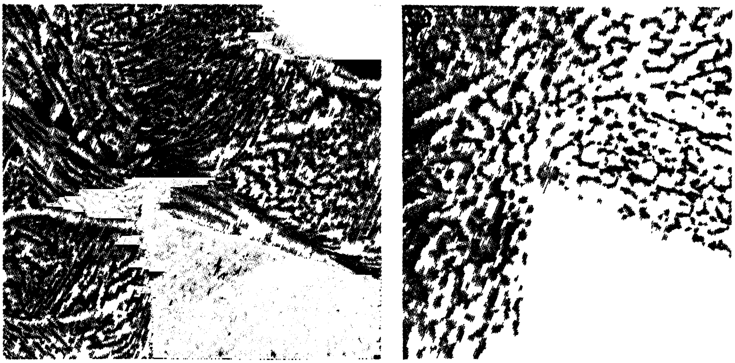


Fig. 2.6. Cutting brass

(*a*) Built-up edge (× 50) (*b*) Same after annealing (× 120)

(*Rosenhain & Sturney*)

It is probable that the base of the built-up edge is permanently seated on the tool face, and that the upper part of the structure alone is affected by the building-up and breaking-down process. A portion of the built-up edge is often observed adhering to the face of a tool after a cutting operation and this suggests that under the influence of the high temperature and pressure at the tool point the base of the edge may become welded to the face of the tool. The adhesion is so great that the point of a sintered carbide tool is often chipped when an attempt is made to remove the built-up edge.

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* *Stahl und Eisen* (1931), **16**, **481**.

The fragments of the built-up edge which adhere to the workpiece are the main cause of roughness on a machined surface in the direction of cutting. These surfaces are sometimes thought to be covered with cracks, but a section parallel to the cutting direction shows that the surface profile has a saw-tooth form, with the steep sides facing in the direction opposite to the motion of the tool. It is usually not so easy to distinguish the fragments of built-up edge on the chip surface owing to the burnishing action of the tool.

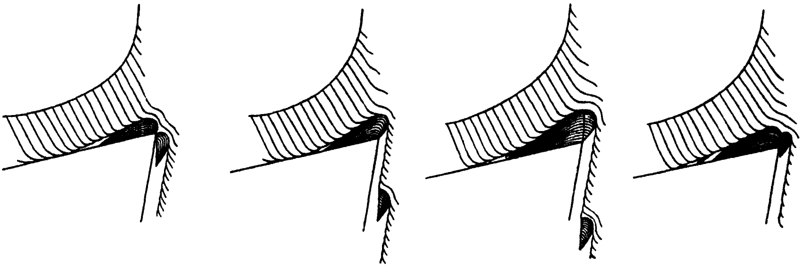

Fig. 2.7. Diagram of the built-up edge cycle

(*Schwerd*)

The built-up edge, besides influencing the surface roughness, also appears to affect the wear of the cutting tool. Since the fragments of the built-up edge are severely work-hardened above the hardness of the parent material, they would be expected to increase the wear of the cutting tool when they passed over the rake and clearance faces of the tool. However, it may be that the presence of a built-up edge reduces tool wear by protecting the tool from continuous contact with the surfaces of the chip and workpiece. Both views have commonly been expressed, but experimental evidence which would demonstrate one or other of the effects to be more important is lacking.

The following factors tend to decrease the size of the built-up edge.* (1) Increase in cutting speed. (2) Decrease in the depth of cut. (3) Increase in rake angle. (4) Application of a lubricant. (5) Increase in the sharpness of the cutting edge.

Schwerd has shown, by photography during the actual cutting process, that an increase in the cutting speed causes a decrease in the size of the built-up edge, and that it disappears above a certain speed. This speed depends upon the other cutting conditions, but it was found when cutting a mild steel with a 15° rake angle and a depth of cut of 0·013 in. that the built-up edge was apparently absent above a speed of approximately 250 ft./min. Microscopic examination of machined surfaces, however, shows that small irregularities which resemble typical built-up edge fragments do occur at higher speeds. It is probable that the change in the size of the built-up edge with cutting speed follows a similar curve to that of surface roughness against speed (Fig. 2.20) but with a displaced zero, and that minute zones of deformed metal can occur at the tool point even at very high speeds.

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* Ernst, H., and Martellotti, M., *Mech. Engineering*, (1935), 57, 487.

The size of the built-up edge decreases with the depth of cut, but it does in fact form with depths of the order of 0·0005 in. such as are obtained in finish broaching.

At relatively slow speeds an increase in the positive rake angle causes a decrease in the size of the built-up edge. If the latter is considered as a separate body resting on the inclined plane of the tool face, it can be seen, in a qualitative way, that an increase in the rake angle would cause it to become less stable with a consequent decrease in its size. At high speeds, however, the temperature generated at the tool point seems to have an effect; under these conditions an increase in the negative rake angle causes a decrease in the size of the built-up edge. (See later under *Roughness of Machined Surfaces.*)

There is a greater tendency for a built-up edge to form when the coefficient of friction between the chip and the tool is high. When a lubricant which reduces the friction coefficient is used, an improved finish of the workpiece results.

Bluntness of the tool which involves a rounding of the cutting edge causes the rake angle at the tool point to have an effective negative value. At slow speeds, therefore, bluntness of the cutting edge encourages the formation of a built-up edge.

Condition of Machined Surface. Besides its geometric roughness, a machined surface has two other important characteristics of interest to the engineer. The material immediately below the surface has, in general, been plastically deformed. It is, therefore, usually harder than the body of the material, and it is also commonly left in a state of residual stress.

Herbert,* and more recently other investigators, have studied the hardness of the chip and surface material. Fig. 2.8 shows that the built-up edge, the chip, and the material adjacent to the finished surface and ahead of the tool point are work-hardened; the maximum hardness occurs at the built-up edge because the plastic strain there is greatest.

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* Herbert, E. G., *Trans. A.S.M.E.* (1926), **48**, 705.

The severity and depth of the sub-surface plastic deformation can be observed in the photomicrographs of sections cut parallel with the cutting direction (Fig. 2.9). The severity of the deformation is greatly affected by the rake angle of the tool (becoming greatest for high negative rake angles), and appears to be proportional to the depth of cut. It can be greatly reduced by the use of a lubricant, but it seems to be unaffected by cutting speed except when the built-up edge causes high local deformation at low speeds. This hardened subsurface material may have significant effects on the performance of machined parts in service.

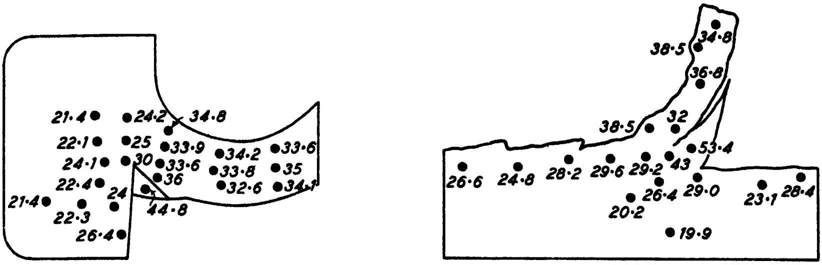
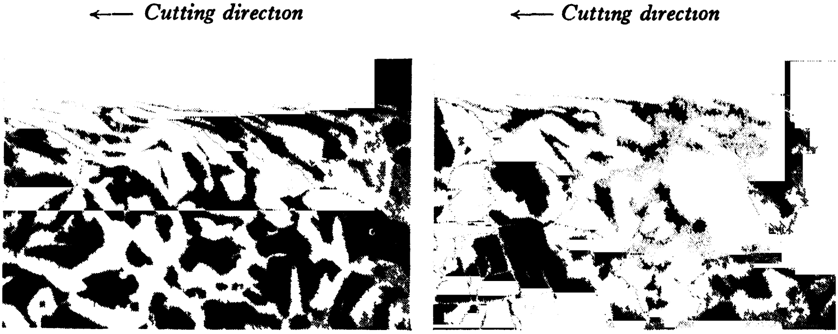


Fig. 2.8. Induced hardness on cutting: (*left*) mild steel; (*right*) stainless steel

(*E. G. Herbert*)



(*a*) *Cutting speed* = 700 ft./min. (*b*) *Cutting speed* = 473 ft/min.

$d = 0.010$ in.

$\alpha = -45°$

Fig. 2.9. The distortion of surface material when cutting mild steel with sintered carbide tools (× 160)

(*Chisholm*)

A number of workers have studied the residual stresses in the material immediately beneath a machined surface. Their existence may easily be demonstrated by machining one face of an annealed plate of material and then observing the resulting distortion of the plate. (Rubbing a thin piece of sheet steel with emery cloth in one direction quickly produces a marked bowing of the sheet, demonstrating a compressive stress in the plane of the sheet but normal to the rubbing direction.) The residual stresses caused by grinding may be as high as the yield point of the work material, and it has been shown that the stresses may change sign (tensile to compressive) more than once as the distance from the surface increases.

These residual stresses seem to be the result of a combination of thermal effects and effects caused by the plastic deformation of the sub-surface material during the cutting or grinding process.

Residual surface stresses, which in extreme cases may cause cracking of the machined part, are also thought to affect the fatigue resistance of machined parts, in the same way that shot peening of components is thought to increase fatigue strength by inducing a compressive residual stress in the sub-surface material.

The Effect of Friction and Lubrication. The friction occurring between the chip and the tool face is a controlling influence in chip formation. The adhesion theory of friction of Ernst and Merchant, and of Bowden and his collaborators at Cambridge, considers that the friction force between a pair of clean metallic surfaces is the sum of *ploughing* and *adhesion* forces. The ploughing force is that required to drag the asperities of one surface through the asperities of the mating surface, and the adhesion force is that required to shear the intermetallic junctions which are formed between the two surfaces at the areas of intimate contact.

When two surfaces are pressed together with a normal load W, the actual area of contact a is usually considerably smaller than the apparent area A. If H is the flow pressure of the softer of the two materials, and S is the shear strength of the intermetallic junctions formed at the areas of actual contact, then, ignoring the ploughing term of friction which is thought to be relatively small, the coefficient of friction $= \frac{F}{W} = \frac{aS}{aH} = \frac{S}{H}$ where F is the friction force. Since S and H are material constants, the friction is proportional to the load and is independent of the apparent area of contact. The adhesion force is much affected by small quantities of surface contamination.

With very clean surfaces, tests carried out in high vacua show that the friction coefficient between metal surfaces can be as high as 6·0 or more.

In the cutting process, the under surface of the chip is a clean freshly exposed surface which is relatively free from adsorbed gases and other contaminating material. The active part of the tool face is also relatively free from a film of contaminating material due to the continual rubbing action of the clean chip surface. The coefficients of friction obtained at the chip-tool interface do not, however, attain the very high values measured by Bowden and Hughes with "degassed" specimens under very high vacua. This may be because of the small quantities of non-metallic inclusions which are present in commercial metals. The values of the friction coefficient found in metal cutting lie in the range 1·2 to 0·2. The friction coefficient is not constant for a particular combination of tool and work materials when cutting dry; it varies considerably with rake angle (increasing with increasing rake angle) and with undeformed chip thickness. The reasons for this are not at present understood.

Ernst and Merchant have shown that the action of certain cutting lubricants depends upon the extreme chemical activity of the very clean surface of the chip in contact with the tool, and that an organic cutting fluid may react directly with the work material to form a compound having a low shear strength and therefore giving a low value of S. Carbon tetrachloride which will not normally react with aluminium, will react with the nascent metal during cutting, giving aluminium chloride, which, having a low shear strength, gives the carbon tetrachloride its lubricating properties. This action is typical of a number of combinations which have been tested. Shaw has demonstrated that certain substances can be prepared commercially in this way, and has termed the process "mechanical activation".

Cutting fluids seem to penetrate to the chip-tool interface by way of the space between the cut surface and the flank face of the tool. Their effectiveness as lubricants decreases as the cutting speed increases. Fig. 2.10 shows how the chip friction angle when cutting copper, using carbon tetrachloride as a lubricant, gradually rises with increasing cutting speed until the value for dry cutting is approached. The effect of the lubricant on the specific cutting pressure (which is equal to the cutting force in the direction of cutting divided by the original cross-sectional area of cut) is considerable at low cutting speeds. The lubricating effects of different cutting fluids can be compared by making measurements of the chip friction angle. How the chip friction angle is determined is shown in the next section.

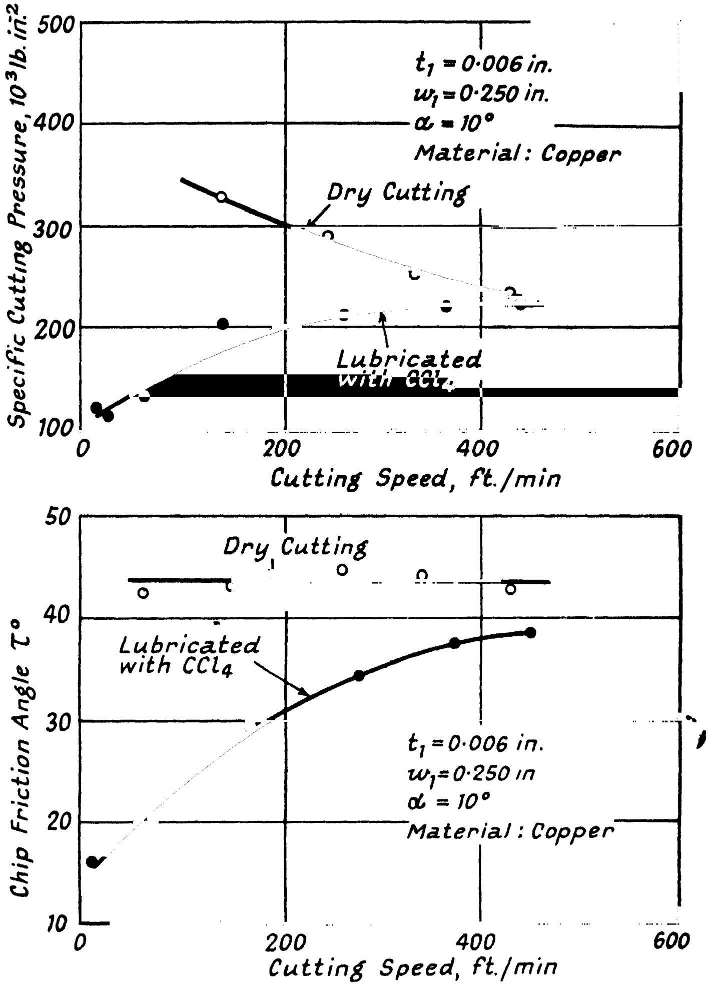
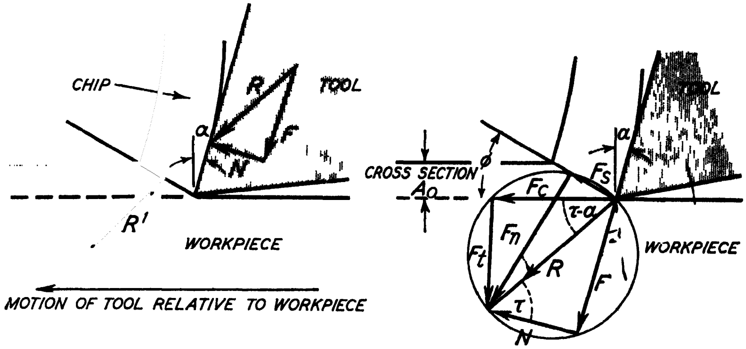


Fig. 2.10. Influence of cutting speed on the effect of a lubricant

(*Chisholm*)

The Mechanics of the Cutting Process. A number of attempts have been made to study the mechanics of the cutting process, starting with Mallock in 1881. It is sufficient here to consider two of the more recent theories.

The theory suggested by Ernst and Merchant and developed later by Merchant, considers a flow-type chip with no built-up edge, and the mode of plastic deformation is considered, on the evidence of photomicrographs showing the process of chip formation, to be simple shear across a plane extending from the tool point to the junction of the chip with the original surface. This type of chip is produced in a reasonable proportion of operations when cutting steel at the high speeds used in modern practice. The theory is confined to the orthogonal case of cutting as previously defined (page 51).



(*a*) Force system acting on chip. (*b*) Resolution of resultant cutting force *R*
Fig. 2.11

The angle between the plane of shear and the direction of cutting is termed the shear angle and is denoted by φ.

The chip (Fig. 2.11*a*) may be considered as a separate body held in equilibrium by the action of a friction force *F* along the tool face, a normal force *N* perpendicular to the tool face, and a force *R'*, equal and opposite to the resultant *R* of the forces *F* and *N*, acting at the base of the chip. The vectors *R* and *R'* are not necessarily collinear, but the resulting couple is neglected. A convenient form in which to consider the geometry of this type of chip is shown in Fig. 2.11*b* in which the origin of the force vectors is located at the tool point. The resultant force *R* of the tool acting upon the chip can be resolved into a number of component forces by the use of the circle having the vector *R* as diameter. It is assumed that for a sharp cutting tool, to which this theory applies, the force due to the rubbing of the clearance face of the tool in the surface of the workpiece is zero. When the tool is worn, however, Burmester has shown that the total cutting force may rise appreciably; part of this increase may be caused by friction at the flank face.

In this problem the shear angle is unknown; Merchant postulated that its value would be that which would make the total work done in cutting the chip a minimum. The total work done in cutting is governed only by the cutting force F_c in the direction of the motion of the tool relative to the workpiece, and the distance cut. By finding an expression for F_c and differentiating with respect to φ, the condition for a minimum value of F_c is obtained.

If α = rake angle of the tool

and $$\mu = \tan \tau = \frac{F}{N} \tag{1}$$

where μ = coefficient of friction between the chip and the tool
and τ = angle of chip friction

then from the geometry of Fig. 2.11*b* the cutting force F_c is

$$F_c = R \cos (\tau - \alpha) \tag{2}$$

and the force across the shear plane F_s is

$$F_s = R \cos (\varphi + \tau - \alpha) \tag{3}$$

Now $F_s = A_s S_s$
where A_s = area of shear plane
and S_s = shear stress across the shear plane

then $$F_s = \frac{A_0}{\sin \varphi} S_s \tag{4}$$

where A_0 = cross-sectional area of chip before removal.
By equations 2, 3, and 4,

$$F_c = A_0 S_s \frac{\cos (\tau - \alpha)}{\sin \varphi \cos (\varphi + \tau - \alpha)} \tag{5}$$

In order to obtain an equation for F_c which is independent of the shear stress, and which depends only upon the shear angle φ and the constants for the system, conditions which regulate the failure of the material under stress must be introduced. The simplest procedure is to assume that the shear strength S_s' is a true constant for the material being cut. On the shear plane during cutting, the shear stress is equal to the shear strength, and therefore

$$F_c = A_0 S_s' \frac{\cos (\tau - \alpha)}{\sin \varphi \cos (\varphi + \tau - \alpha)}. \tag{6}$$

To find the value of φ which makes F_c (and therefore the work done) a minimum, this expression is differentiated with respect to

φ, and $\frac{\partial F_c}{\partial \varphi}$ equated to zero. The condition for minimum F_c which is obtained is given by the equation

$$2\varphi + \tau - \alpha = 90^\circ \quad . \quad . \quad . \quad . \quad (7)$$

Merchant introduced a modification to this theory and assumed that the shear strength of a polycrystalline metal varied as the normal pressure on the plane of shear. That is

$$S_s^1 = S_0 + kS_n \quad . \quad . \quad . \quad . \quad (8)$$

where S_0 and k are constants for the material and S_n is the normal stress on the shear plane. Substituting this in equation (5), and eliminating S_n, the condition for minimum F_c can again be found, namely:

$$2\varphi + \tau - \alpha = \cot^{-1} k \quad . \quad . \quad . \quad (9)$$

Lee and Shaffer in 1949 obtained a solution to the problem of the mechanics of orthogonal cutting by using the slip-line field theory which was developed for studying the stress distributions in a body

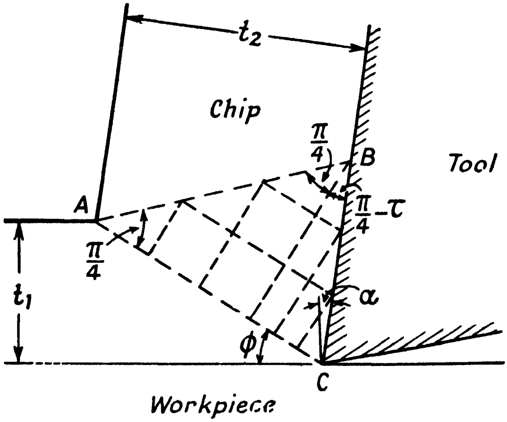


Fig. 2.12. Slip-line field solution with no built-up edge (*after Lee & Shaffer*)

undergoing plastic deformation in two dimensions. The development of this solution cannot be treated here, and it is sufficient to outline its main features as shown in Fig. 2.12.

The material is considered to be ideally plastic, that is, it is rigid until it yields and then does not work-harden. The region *ABC* is called a slip-line field and defines that part of the chip which is plastic at the instant of yield. The slip lines themselves are lines of maximum shear stress, and discontinuities in shear strain can occur tangentially to them. To be valid, a slip-line field solution must satisfy the stress equilibrium conditions and the assumed behaviour of the material. From the geometry of the solution given in Fig. 2.12, the following relationship can be obtained:

$$\varphi + \tau - \alpha = 45° \quad . \quad . \quad . \quad . \quad (10)$$

Lee and Shaffer also proposed a solution which incorporated a built-up edge, and the resulting relationship between φ and $(\tau - \alpha)$ lies mainly between the first Lee and Shaffer solution and the solution $2\varphi + \tau - \alpha = 90°$.

In order to compare the predictions of equations (7) and (9) with experiment, it is necessary to be able to determine φ and τ experimentally.

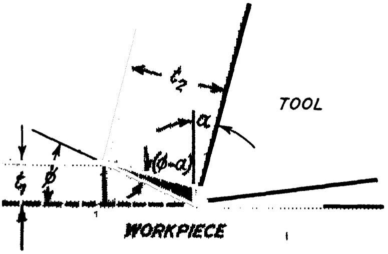


Fig. 2.13. Determination of chip thickness ratio

If in Fig. 2.13 it is assumed that the width of the chip remains the same before and after cutting, and t_1 = thickness of chip before removal (the undeformed chip thickness) and t_1 = thickness of chip after removal, then the chip thickness ratio

$$r_c = \frac{t_1}{t_2} = \frac{L_2}{L_1} = \frac{\sin \varphi}{\cos (\varphi - \alpha)} \quad . \quad . \quad . \quad (11)$$

where L_1 and L_2 are the lengths of the chip before and after cutting.

$$\text{Hence,} \quad \tan \varphi = \frac{r_c \cos \alpha}{(1 - r_c \sin \alpha)} \quad . \quad . \quad . \quad (12)$$

When r_c has been determined experimentally, φ can be calculated. From Fig. 2.11, it can be seen that

$$(\tau - \alpha) = \tan^{-1} \frac{F_t}{F_c} \quad . \quad . \quad . \quad . \quad (13)$$

The force components F_t and F_c can be determined experimentally and hence the friction angle τ derived.

Fig. 2.14 shows a plot of experimental results compared with the relations of equations (7) and (10). It has been found that in general neither of these relationships accurately predicts what actually occurs, the experimental relationship obtained being apparently very dependent upon the work material. The relationship of equation (8) is no improvement because the evidence indicates that the effect of normal stress on shear strength (if one exists) is too small to account for the observed discrepancy. There is therefore at present no satisfactory theory of the mechanics of the cutting process, though the existing theories do predict qualitatively, and correctly, that a decrease in the chip friction coefficient should result in an increase in the shear angle.

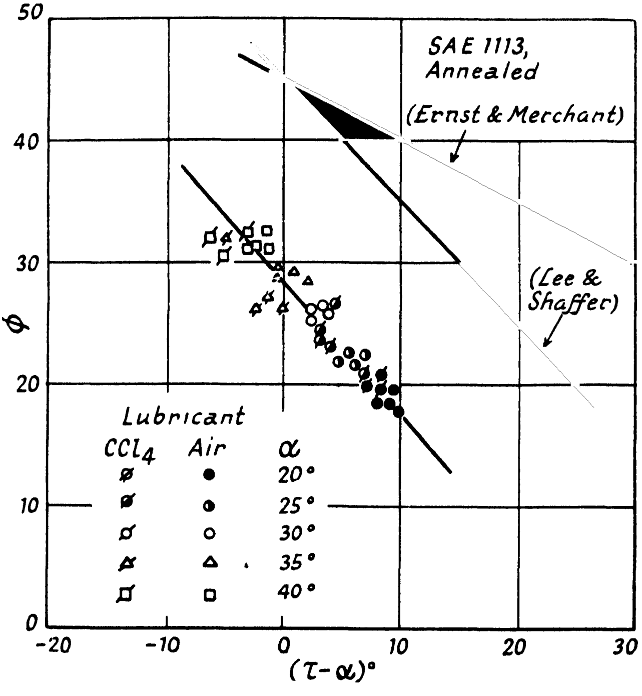


Fig. 2.14. Experimental and theoretical relations between φ and $(\tau - \alpha)$

By experimentally determining the quantities F_c, φ, τ and α, it is possible, using equation (5), to estimate the shear strength of the work material as it is exhibited in the cutting process. Kececioglu has recently shown that this shear strength remains fairly constant over a wide range of cutting conditions, and that the strain rate at the shear plane is about $2{\cdot}0 \times 10^5$ per sec. at a cutting speed of 750 ft./min. when cutting a low-carbon steel.

Cutting Temperature. The temperatures at the shear plane, at the chip-tool interface, and at the rubbing surface of the clearance face of the tool, are all significant factors in the study of type of chip formation, the cutting forces, the tool wear, and the surface produced.

So far no satisfactory method has been evolved for measuring these temperatures experimentally. Some investigators have obtained the mean chip temperature by catching the chips in a calorimeter, but this gives no idea of the temperature gradient across the chip or the temperature at the shear plane. Herbert was probably the first to use a thermo-electric method to measure the temperature at the junction of the tool with the chip and workpiece. The dissimilar metals of tool and workpiece generate a thermo-electric e.m.f. which can be calibrated in terms of temperature. The temperature measured by this means appears to be a mean of the temperatures at the sliding surfaces of the work surface-clearance face and the chip-tool interfaces. Temperature-sensitive paints have been used, and radiation pyrometers have been developed to measure the surface temperature at the side of the chip and workpiece. Thermocouples have also been inserted into the cutting tool. All these methods suffer from the disadvantage of being unable to follow the steep temperature gradients which occur near the surfaces of the cutting tool.

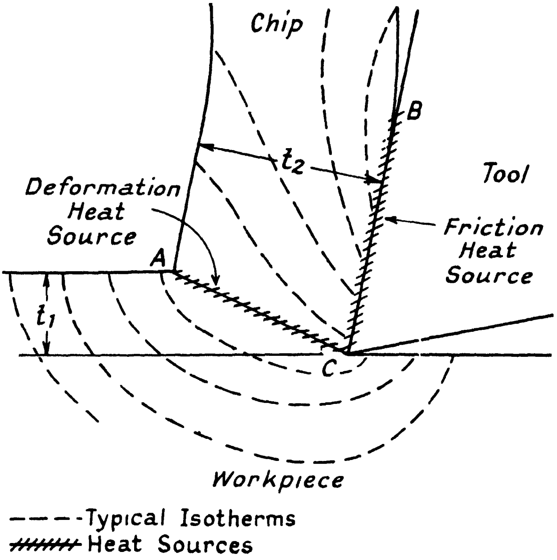


Fig. 2.15. Temperature distribution in chip and workpiece (*after Rapier*)

Several investigators have for this reason attempted analytical treatments of the heat conduction problem in the cutting process, and Rapier* has developed a technique based on a relaxation method for estimating the temperature distribution in the chip, tool and workpiece. It may be assumed that all the energy of cutting is converted into heat: the work done in plastic deformation at the shear plane at *AC* (Fig. 2.15) and the work done against friction at the chip-tool interface *BC*. The quantities of heat can be estimated from experimental measurements of F_c, F_t and r_c. The type of temperature distribution obtained in the chip and workpiece is shown.

Vibration of Cutting Tools. Vibration of the cutting tool or workpiece is generally known as chatter. Though chatter marks on a machined surface may be caused by imperfections in the driving gears or the machine bearings, only vibration caused by the characteristics of the cutting action will be considered here.

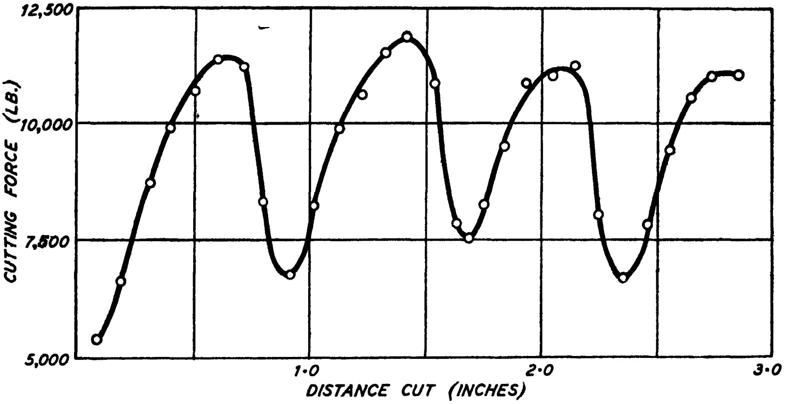


Fig. 2.16. Periodic variations in the cutting force when cutting a discontinuous type chip

Rake angle = 30°. *Cutting speed* = 1·65 ft./min. *Depth of cut* = 0·41 in. *Material*, medium carbon steel. Feed per rev. = 0·125 in.

(*Dempster Smith*)

Vibrations of this type have been explained by two theories. The first depends upon the cyclic variation in cutting force which occurs during the removal of a discontinuous type chip. When the frequency of these force variations becomes nearly equal to some natural frequency of the tool or the workpiece the system approaches a state of resonance, and chatter results. The severity of vibration is thought to depend upon how closely the frequency of the disturbing force coincides with the natural frequency of the tool or the workpiece system. Dempster Smith measured the cyclic variations in force when cutting steel at different speeds and showed that the fluctuations in force at very slow cutting speeds were of the type shown in Fig. 2.16, the force waves being caused by the removal of successive chips. Owing to the decrease in response of the mechanism used for recording the variations in force with increased frequency, it was found impossible to measure the precise effect of increasing the cutting speed on the amplitude of these force fluctuations. By an examination of the chips it was deduced, however, that the total variation in force decreased as the cutting speed increased, the force tending to a constant value at a particular cutting speed depending upon the size of the cut being made. With $\frac{1}{4}$ in. depth of cut and $\frac{1}{8}$ in. feed this speed was approximately 80 ft./min. when cutting mild steel in alathe.

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* *British J. of Appld. Physics.*

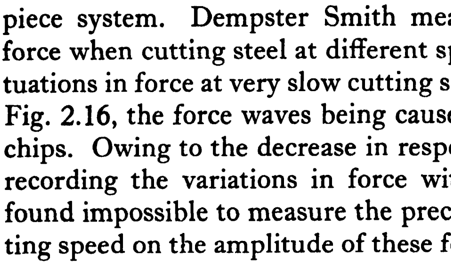

Fig. 2.17. Typical relation between cutting force and cutting speed

Although periodic variations in the cutting force caused by the successive shearing of the chips may cause vibration in some special cases, a more general explanation of chatter phenomena has been given by Den Hartog and confirmed by the experimental investigations of Arnold.* They class the chatter of a cutting tool with the vibration of a violin string, and show that theoretically a vibration of a cutting tool can be established because of the negative slope of the curve relating cutting force and cutting speed (Fig. 2.17). Consider the simple harmonic vibration of a cantilever cutting tool at its natural frequency $\frac{\omega}{2\pi}$.

Let the amplitude of the tool point be x_0, and let the tool be cutting the material at a mean speed of V.

The displacement of the tool point $x = x_0 \sin \omega t$,

and the velocity of the tool point $\frac{dx}{dt} = \omega x_0 \cos \omega t$.

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* *Proc. Inst. Mech. Eng.* (1946), **3**, 154, 261, and Chisholm, A. J., **4**, 429.

The velocity of the workpiece relative to the tool (Fig. 2.18) varies between $(V + \omega x_0)$ and $(V - \omega x_0)$.

The forces acting on the tool at a particular value of relative cutting velocity may be obtained from the force-speed curve in Fig. 2.17. When the tool is moving downwards through the mid-position, the relative velocity is $(V - \omega x_0)$, and the force acting on the tool is P_1. When the tool is moving upwards through the mid-position, the relative velocity is $(V + \omega x_0)$ and the force is P_2. Now P_1 is greater than P_2, so that the greater force acts in the direction of motion of the tool. A net amount of work is therefore done on the vibratory system in a cycle, and if this energy is greater than the amount of energy lost from the system per cycle due to positive damping, then the amplitude of vibration will tend to increase, and the vibration is said to be *self-excited.*

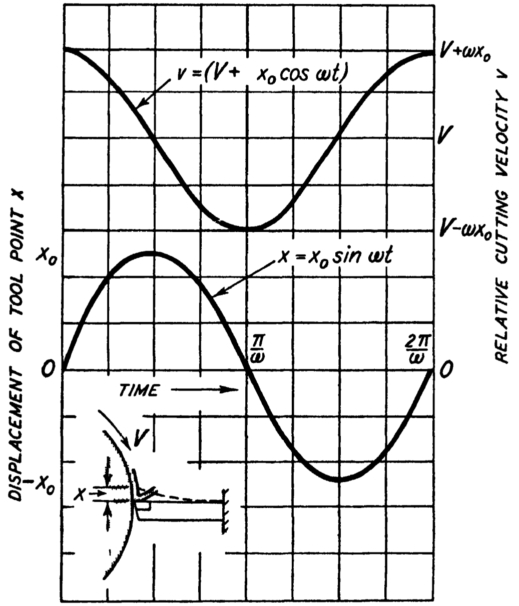

Fig. 2.18. Variation in relative cutting speed

Arnold found a number of characteristics relating to the chatter of a cantilever lathe tool when arranged relative to the work as shown in Fig. 2.18.

(1) The amplitude of vibration cannot exceed a value slightly in

excess of $x_0 = \dfrac{V}{2\pi f}$ where V = cutting speed, inches per second, and f = natural frequency of tool, cycles per second.

(2) Wear on the clearance face of the tool appreciably increases the tendency to vibrate. This is because the flank face of the tool interferes with the machined surface in a way favourable to increasing the energy of vibration.

(3) The vibration is affected by the overlap of the tool on the chatter profile cut in the previous revolution of the workpiece (in a lathe). The tool is thus subjected to a small additional periodic force which causes an increase in the tendency to vibrate. The frequency of this periodic force is very nearly equal to the frequency of the vibrating cutting tool, and the cutting tool is therefore in resonance with the disturbing force. The definite phase relationship which results between the displacement and the disturbing force produces the familiar chatter patterns (Fig. 2.19).

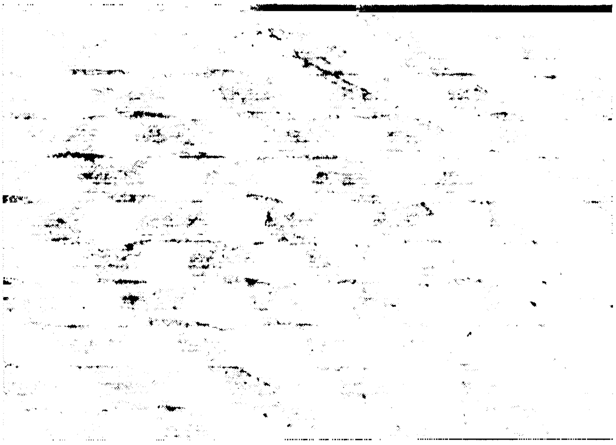

Fig. 2.19. Chatter patterns obtained on heavy planing machine

Frequency = 6 cycles per sec. *Cutting speed* = 17 5 ft./min. *Depth of cut* = $\frac{7}{16}$ in. *Feed* = 0 020 in.

(*Arnold*)

(4) There is a limit of cutting speed below which vibration will not occur; this increases as the natural frequency of the tool increases.

More recently, other investigators have studied the mechanism and have confirmed that it is of the self-excited type. It is evident, however, that the mechanism which actually operates in a particular case depends upon the geometric relationship of tool to work and their elastic behaviour. (A lathe tool presented laterally to the workpiece behaves differently from one presented end-on as in Arnold's experiments.)

In practice, large cutting forces, a negative rake angle, a broad thin chip (caused by a small approach angle on a large nose radius) tend to produce chatter. One positive way of preventing chatter is to introduce damping into the sytem. Hahn, for example, has developed a loose-mass damper for use in a boring bar.

Roughness of Machined Surfaces. This is affected by the conditions of cutting, and the optimum conditions for the production of smooth surfaces direct from the cutting tool are of great general interest. Improvements may be sought (*a*) by modifying the process of chip formation, and (*b*) by considering the geometry of the tool profile in relation to the feed. The factors involved in (*a*) are considered first.

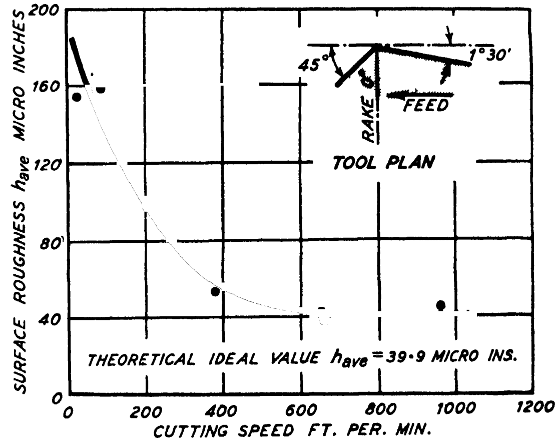

Fig. 2.20. The effect of cutting speed on surface roughness when turning mild steel with a sintered carbide tool

Depth of cut = 0·015 in. *Feed* = 0·006 in. *Rake angle* = 0°

Speed and Rake Angle. With ductile materials which normally produce continuous chips, a reduction in the size of the built-up edge appears to reduce the size of the fragments adhering to the workpiece. With materials which produce only discontinuous chips, waves are found on the surface corresponding to the frequency of shear, but this has not yet been fully investigated.

Fig. 2.20 shows that, for mild steel, with increasing cutting speed the h_{ave} value of surface roughness, measured parallel to the axis of the workpiece (see *Surface Technology*, Chapter XVII), decreases and approaches a specific minimum value at the "optimum cutting speed" at which the effect of the built-up edge is practically negligible. The profile of the true cutting edge of the tool is then reproduced on the work surface at the appropriate feed. This *ideal* surface roughness may be calculated from a knowledge of the cutting-edge profile and the feed of the machine (Fig. 2.23). The remarkable agreement between the theoretical value and the minimum measured values of roughness (Fig. 2.20) will be noticed.

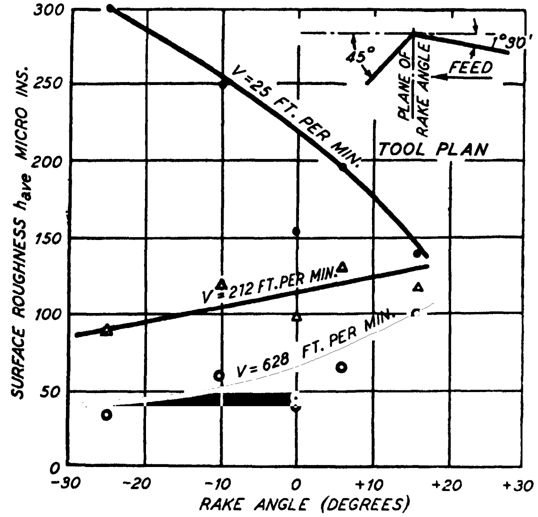

Fig. 2.21. The effect of rake angle and cutting speed on the roughness of turned surfaces

Depth of cut = 0·015 in. *Feed per rev.* = 0·006 in.
Material = mild steel. *Sintered carbide tools*

The effects of rake angle on the roughness are shown in Fig. 2.21. At slow speeds the roughness decreases as the positive rake angle increases, the tool becoming more acute, but at high speeds the roughness decreases as the negative rake angle increases. These effects may also be explained by the effect of speed and rake angle on the formation of the built-up edge.

Galloway has shown that when turning cast aluminium alloys with sintered carbide tools, the curve relating roughness and cutting speed is U-shaped, rising again after the minimum value. Extruded aluminium alloys did not behave in this way, however, and the explanation of these apparently conflicting results must lie in the characteristics of chip formation for both the tool material and the material being cut.

LUBRICATION causes a decrease in the roughness of a machined surface by decreasing the friction at the chip-tool interface, and consequently by reducing the size of the built-up edge. The effectiveness of the lubricant in lowering the friction decreases quite rapidly as the cutting speed increases (Fig. 2.10), so it is fortunate that the need for a lubricant, as distinct from a coolant, is reduced as the speed increases, owing to the decrease in the size of the built-up edge which normally occurs with increasing cutting speed. As there may be intermediate speeds at which the lubricant is insufficiently effective but the speed is not sufficiently high to cause an acceptable degree of smoothness, it may then be necessary either to increase the cutting speed or to reduce the speed to a low value and to use a lubricant.

TOOL MATERIAL. A change in the tool material, by altering the friction at the chip-tool interface, may affect the roughness of the cut surface. The coefficients of friction between the chip and the tool* are substantially different for high-speed steel and diamond tools when cutting a number of different materials. When cutting steel, copper, and aluminium, they are found to be lower for diamond tools than for those of high-speed steel. A better surface finish would therefore be expected from diamond tools when cutting these materials. It is probable that the different finishes produced by different grades of cemented carbide cutting tools are associated with their frictional characteristics. The good finish produced by sintered oxide cutting tools may also be associated with this.

SURFACE ROUGHNESS OF TOOL FACES. It has been suggested (page 62) that the *ploughing* term of friction due to the surface asperities is small in comparison with the *adhesion* term, owing to the extreme cleanliness of the rubbing surfaces, so the friction between the chip and the tool should not be appreciably affected by the surface roughness of the tool face. The effect which the surface finish of the tool face has on the smoothness of the machined surface is probably not due, therefore, to changes in friction but to the condition of the cutting edge. If the clearance and top faces of the tool are rough, then the cutting edge shares this roughness, and a poorly finished tool not only reproduces its ragged profile on the finished surface but also tends to form a site for the formation of a built-up edge.

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* Grodzinski, P., *Diamond Tools*, p. 214. N.A.G. Press, Ltd., London, 1944.

Ideal Surface Roughness. A surface generated exactly by the tool has a roughness which may be termed *ideal.* With a turned

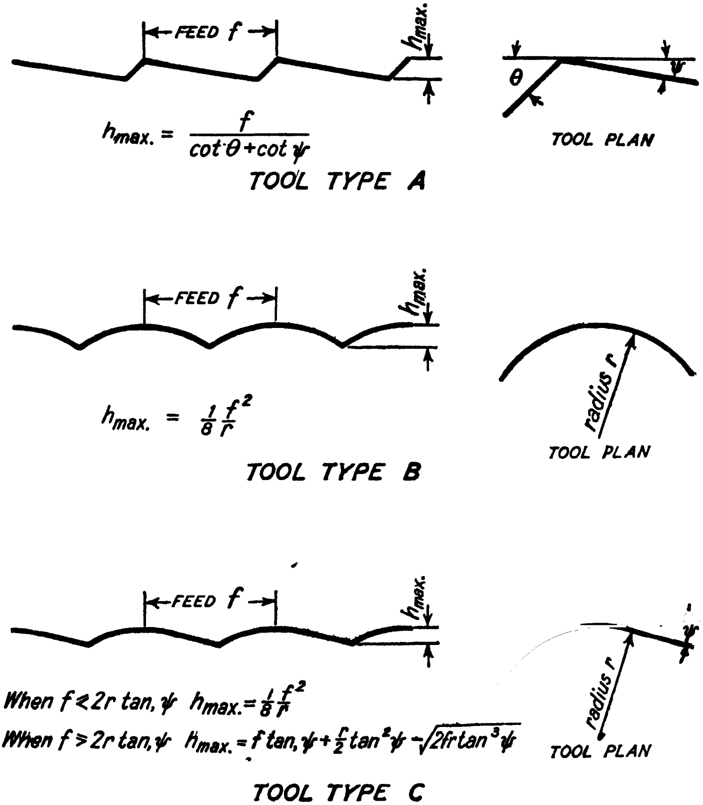
FEED f
$h_{max.}$
$h_{max.} = \frac{f}{\cot\theta + \cot\psi}$
TOOL TYPE A
θ
ψ
TOOL PLAN
FEED f
$h_{max.}$
$h_{max.} = \frac{1}{8}\frac{f^2}{r}$
TOOL TYPE B
radius r
TOOL PLAN
FEED f
$h_{max.}$
When $f \leq 2r\tan\psi$ $h_{max.} = \frac{1}{8}\frac{f^2}{r}$
When $f \geq 2r\tan\psi$ $h_{max.} = f\tan\psi + \frac{r}{2}\tan^2\psi - \sqrt{2fr\tan^3\psi}$
TOOL TYPE C
radius r
ψ
TOOL PLAN

Fig. 2.22. Ideal values of roughness for turned surfaces

surface, the ideal surface roughness depends upon the plan angle of the tool, its nose radius, its horizontal end clearance angle, and the feed of the machine. Wear of the tool profile as the cutting proceeds will, of course, cause the surface to differ somewhat from the ideal.

Fig. 2.22 shows the ideal values of h_{max} (the root to crest value of roughness) for three types of cutting edge. Fig. 2.23 shows calculated curves relating the ideal roughness h_{max} with the feed per revolution. For the sharp-nosed tool (type A) the roughness is extremely sensitive to changes in the horizontal end clearance angle. With a round-nosed tool (type B) the roughness is inversely proportional to the nose radius, and the addition of a straight trailing edge to the tool (type C) has no effect below a certain value of feed. It is general practice in turning fine surfaces to use a tool of type C and to make the horizontal end clearance angle ψ as nearly equal to zero as possible. The curves indicate that this type of tool must be set in plan very accurately if the desired effect is to be obtained. For this reason the round-nosed tool, whose performance is practically independent of its setting, has definite advantages.

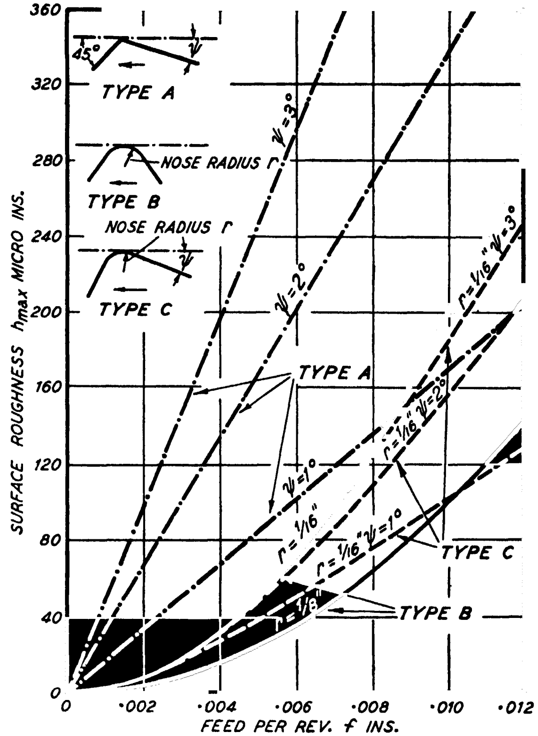

Fig. 2.23. The effect of tool-plan contour on the ideal roughness of turned surfaces

Cutting Forces acting on a Single-point Tool

Component Cutting Forces. The forces acting on a cutting tool are of fundamental importance in the design and use of cutting and machine tools. In a turning operation with a single-point tool the resultant cutting force *R* acting on the tool is usually considered as the vector sum of three component cutting forces mutually at right angles: the tangential force F_t tangential to the surface of the workpiece at the tool point and perpendicular to the direction of feed, the feeding force F_f, and the force normal to the surface F_n (Fig. 2.24).

Dynamometers have been designed for measuring one or more of the components, and have been used in extensive investigations to

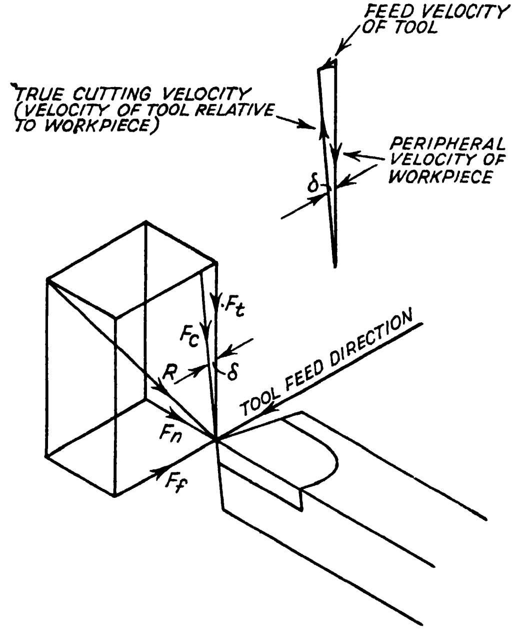
FEED VELOCITY OF TOOL
TRUE CUTTING VELOCITY (VELOCITY OF TOOL RELATIVE TO WORKPIECE)
PERIPHERAL VELOCITY OF WORKPIECE
δ
F_t
F_c
R
δ
F_n
F_f
TOOL FEED DIRECTION

Fig. 2.24. Components of cutting force for turning operation

determine the power and forces involved in cutting. The cutting forces are arranged to deflect mechanical springs, usually in the form of stiff diaphragms, the deflections of which are measured either by electrical or mechanical means and which, by calibration, give values of the forces acting.

The cutting force F_c acting in the true direction of cutting, multiplied by the true cutting velocity gives the power absorbed in cutting. In a turning operation the feed is small compared with the distance cut in the direction of the tangential force and therefore the power required for feeding may generally be neglected. Horsepower is given approximately by,

$$\text{Horsepower} = \frac{F_t V}{33000}$$

where F_t = tangential cutting force in pounds
V = surface cutting speed in ft./min.

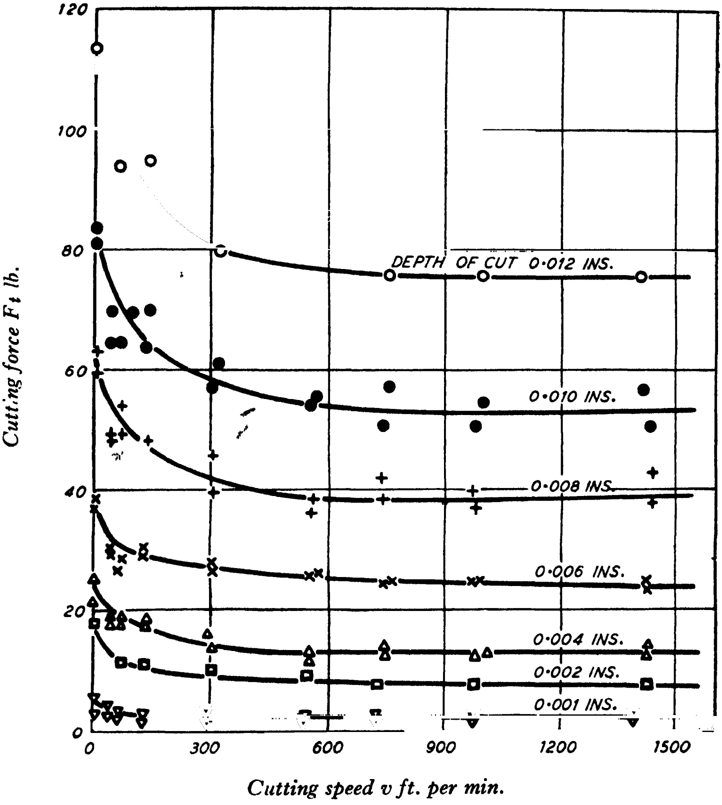

Fig. 2.25. Relation between force and speed when cutting a bronze

Width of cut = 0·040 in. *Rake angle* = 0°. *Sintered carbide tools*

The following paragraphs deal with the effect of the cutting conditions on the force F_c. In some cases the experimental results quoted refer to the tangential force F_t, but since this is very nearly equal to F_c the conclusions are virtually unaffected. It has been found desirable to indicate general trends in the cutting force rather than to attempt to give exact laws governing its behaviour under all conditions. The subject is too complicated and the experimental information too incomplete for such laws to be stated.

Cutting Speed. The effect of speed on the cutting force varies with the condition of cutting. Although it has generally been assumed that over the ranges of speed used in practice the cutting force is independent of speed, experimental results have shown that this is not strictly correct.

Arnold and the writer have shown that when cutting mild steel and bronze the force decreases as the speed increases in the lower range of cutting speeds (Fig. 2.25) and thereafter remains approximately constant. These results do not agree completely with those of certain other investigators.

Merchant has shown that when cutting a steel with sintered carbide tools in the normal practical range of speed, the effect of speed on the cutting force depends upon the rake angle of the tool. With a −10° rake tool the cutting force decreases, whereas with a positive rake tool the force remains more nearly constant. There is no evidence to suggest that negative rake tools ever require a smaller force than positive rake tools under corresponding conditions.

Feed and Depth of Cut. The cutting force does not vary directly as the cross-sectional area of the cut. In turning mild steel, if the area of cross-section of the cut remains constant, a minimum cutting force occurs when the depth of cut is approximately equal to the feed per revolution (Fig. 2.26). Cutting force does not in general increase linearly with *undeformed chip thickness.* Fig. 2.27 shows that the specific cutting force decreases as the undeformed chip thickness increases. Shaw has suggested that this "size effect" is the result of the dimensions of the material being deformed in cutting becoming comparable with the average spacing of imperfections in the metal structure. When this happens the strength of the metal begins to increase towards its

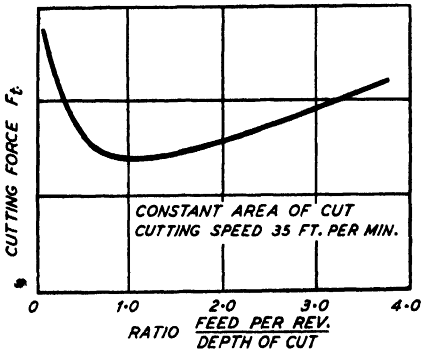

Fig. 2.26. The effect of shape of cut on cutting force when cutting a mild steel

(*Dempster Smith*)

theoretical strength; this is very much greater than the strength of metals observed normally in practice.

Rake and Clearance Angles. The effect of increasing the rake angle is to decrease the cutting force. Increasing the rake angle decreases the chip thickness (even though the chip friction coefficient is also increased), and the work done in shear deformation is therefore reduced. The overall effect is a reduction in total cutting energy.

Work by Armitage and Schmidt* showed that the mechanical strength of the negative rake tool could be combined with the low-power consumption of the positive rake tool by using a positive rake tool with a small negative rake *land* ground on the face of the tool adjacent to the cutting edge. The land was found to affect the cutting force only slightly.

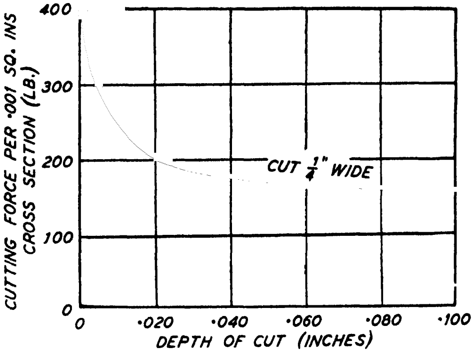

Fig. 2.27. Relation between cutting force per unit area of cross-section and depth of cut in a planing operation

Rake angle = 30°. *Cutting speed* = 20ft./min. *Material* = mild steel

(*Boston*)

Merchant and Boston have shown experimentally that the component cutting forces are unaffected by the clearance angle.

Tool Bluntness. The bluntness of the cutting edge has a variable effect depending whether or not a built-up edge formation is situated at the tool point. Boston has stated that deliberate blunting of the cutting edge up to $\frac{1}{64}$ in. radius has little effect upon the cutting force when cutting steel at a speed of 20 ft./min. At this speed the tool point serves only to support the built-up edge and it would therefore be expected that a rounding of the cutting edge would have no appreciable effect upon the process of chip formation. At high speeds, when the built-up edge is either extremely small or non-existent, bluntness of the edge may have a greater effect. It has already been stated that Burmester found a marked increase in the cutting forces with increase in tool wear.

Lubrication and Tool Material. At relatively low cutting speeds an appreciable reduction in the cutting force can be obtained

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* *Mech. Engineering* (1945), 67, 403; also *Trans. A.S.M.E.* (1944), 66, 633.

by the use of a lubricant as shown in Fig. 2.10, but the effectiveness of a lubricant decreases as the speed increases. Extensive work on the effect of various cutting fluids on drilling torque has been carried out.

Very little work has been done on the effect of tool material on the cutting force. Some variation does occur due to the change in the coefficient of friction between different pairs of materials. The cutting forces for diamond tools are, in some cases, appreciably smaller than the cutting forces for high-speed steel tools.

FORMULAE FOR CUTTING FORCES. A number of investigators have attempted to derive empirical formulae for cutting force. These formulae are based on large numbers of tests and are meant to provide workable relations for determining the cutting forces under any set of conditions, but the difficulties associated with metal-cutting experiments, and the large number of variables involved, make the derivation and use of such formulae an uncertain procedure. For example, in a conventional turning operation there are at least twelve variables, excluding tool wear, which influence the cutting force, and since each variable is a possible source of error, the calculated values must be treated with some reserve. The formula in the A.S.M.E. *Manual on Cutting of Metals* is as follows:

$$P_t = K_p K_a T^c L^d$$

where P_t = tangential cutting force,
K_p = constant depending upon the material cut,
K_a = constant depending upon the true rake angle of the tool,
T = average chip thickness,
L = length of cutting edge in active engagement

and c and d are exponents depending upon the material being cut.

The variables T and L are introduced in order to embrace the nose angle, nose radius, feed per revolution, and depth of cut.

In general, the effects of the operating conditions on the cutting force may at least partially be explained in qualitative terms by considering the effects of chip friction and rake angle on the chip thickness (equations 11–13), and therefore on the work done in plastic deformation on the shear plane and the work done against friction on the tool face.

Tool Wear

TYPES OF WEAR. The wear of a cutting tool may be classified into two main types—a gradual loss in dimension and weight, and a *spalling* or crumbling of the cutting edge due to local mechanical fractures in the tool material. The recognition of these two types of wear in practice is a prerequisite to using the current grade for a particular job. Small fractures along the cutting edge indicate that a tougher tool material is required.

Gradual wear occurs both in the flank face and the rake face of the tool where a *crater* forms (Fig. 2.28). Complete failure of a cutting tool occurs when the clearance wear breaks into the crater and causes the cutting edge to collapse.

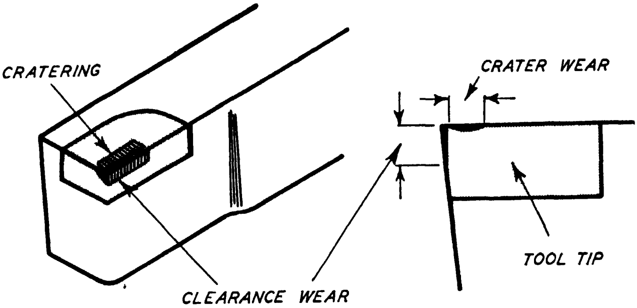

Fig. 2.28. Tool wear

The factors governing the wear of cutting tools are not properly understood; so many variables are involved that it is probable that a number of different mechanisms operate simultaneously. It is therefore important not to oversimplify, and believe, for example, that the hardness of the tool material is the sole criterion of its wear resistance.

Recently, Trent* made an important contribution to our knowledge of tool wear, and showed why relatively small additions of titanium carbide to a cemented tungsten-carbide tool material considerably improved the resistance of these materials to crater wear when cutting steel. He found that when samples of steel and a tungsten carbide tool material were placed together in contact, the tungsten-carbide reacted with the steel at a temperature of between 1300° C. and 1325° C. forming a molten phase which was absorbed into the cemented carbide test-piece. At 1325° C. a test-piece of a cemented carbide tool material containing tungsten-titanium carbide was practically unattacked by steel. Trent therefore postulated that when cutting steel with tungsten-carbide tools, the high temperatures generated on the rake surface allowed the steel chip to wear away the tungsten carbide by chemical attack. It has been found that the temperatures expected on the tool rake surface are of the right order, and the temperature distribution is of the right kind, to produce a crater of the observed type.

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* Trent, E. M., *Proc. Inst. Mech. Eng*, 1952, **166**, 64–74.

Experiments with radioactive tracers have shown that material is removed from the surfaces of the cutting tool in minute discrete blobs, and is transformed to the under-surface of the chip and the freshly cut surface. This transfer of material could be the result of the shearing of the intermetallic junctions formed when two surfaces rub together. Information is lacking on how such factors as friction and the cutting temperatures affect flank and crater wear, but the effects of the operating conditions—tool shape, cutting speed, etc.—are discussed in the following sections. Abrasive particles (e.g. carbides, oxides, nitrides) in the work material affect tool wear, and aluminium, used as a deoxidizer in steel manufacture, has a noticeably bad effect on tool wear even when used in the proportion of $\frac{3}{4}$ lb. per ton of steel. The aluminium appears as aluminium oxide particles which are very hard. The soft manganese sulphide particles in steel, and lead which is added to improve machinability, reduce the rate of tool wear by lowering the friction between chip and tool, which in turn reduces the cutting force.

While crater wear is the preponderant type of tool wear with certain tool and work materials under certain cutting conditions, with other materials and under different conditions, flank wear is the more important. The factors governing the preponderance of one type on the other are not yet understood.

CRITERION OF TOOL LIFE. The total tool life and the cutting time between regrinds are generally more important factors, economically, than the cost of the power consumed by the machine tool. Tool life is a difficult factor to define adequately but in experimental work to determine the effect of different conditions on wear, tool life has generally been taken as the cutting time required for complete failure of the tool, or as the time necessary to produce a given amount of flank wear on the tool. In practice, however, to allow the tool to fail completely before regrinding may be uneconomical owing to the considerable regrinding necessary to restore the tool to a usable form, and consideration of the surface finish, dimensional accuracy of the finished job, or chatter vibration, may entail regrinding after only a fraction of the time required for complete breakdown.

CUTTING SPEED AND TOOL LIFE. Experimental investigation has shown that for a constant size of cut the following emprical law is true,

$$VT^n = C$$

where V = cutting speed,
T = cutting time to tool failure

and n and C are constants depending upon the tool and work materials. The appropriate or ***permissible cutting speed*** at which an operation must be carried out in order that the tool life before tool failure may have a specified duration can be read off from a curve relating to that particular operation (Fig. 2.29). The permissible cutting speed for a definite tool life (for example V_{60} is the speed for a tool life of sixty minutes), is used in the following as a measure of the durability of a tool under different cutting conditions. It is important to realize that, usually, the corresponding percentage increase in the permissible cutting speed for a given tool life is appreciably smaller than the percentage increase in tool life at a constant cutting speed.

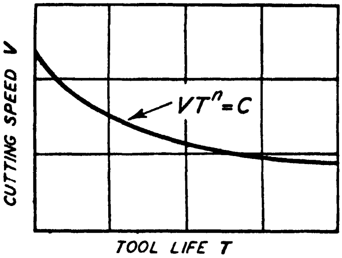

Fig. 2.29. Relation between cutting speed and tool life

Depth of Cut, Feed, Plan Angle and Nose Radius. Experiments performed by Dempster Smith show that the curves relating depth of cut and permissible cutting speed, and the feed and permissible cutting speed in turning operations are similar to one

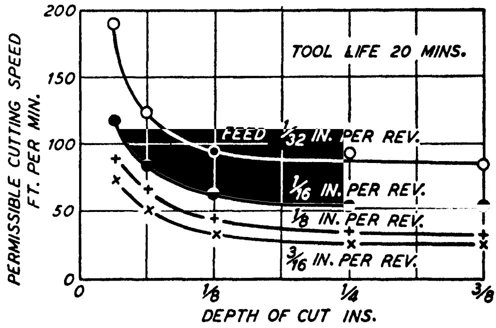

Fig. 2.30. Experimental relation between permissible cutting speed and depth of cut when turning mild steel

Rake angle = 20°. *Tool material* = high-speed steel another; the former relationship is shown in Fig. 2.30. The general effect of the plan angle in turning operations on the rate of tool wear is illustrated in Fig. 2.31, where it is shown that the permissible cutting speed decreases as the plan angle is increased. Dempster Smith has shown also that for a given feed and depth of cut the permissible cutting speed increases as the nose radius of the tool becomes larger.

These results may be explained almost completely by considering the geometry of these turning operations in terms of the basic orthogonal and oblique operations. The fundamental dimension of the cut which affects the rate of tool wear is the average *undeformed chip thickness* measured perpendicular to the cutting edge and perpendicular to the cutting direction; as would be expected, the width of the cut measured along the cutting edge has very little effect on the rate of tool wear. Results of tool-life tests such as those of Fig. 2.30, when replotted in the appropriate manner, show that the permissible cutting speed is a single function of the average undeformed chip thickness, and depends only upon the feed, depth of cut, plan angle, or nose radius in so far as these factors affect the undeformed chip thickness. This illustrates the importance of considering the correct dimension of the chip when considering rates of tool wear, not only in turning operations, but also in drilling and milling operations, etc.

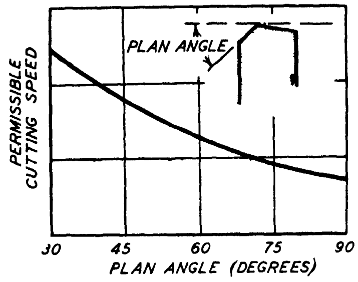

Fig. 2.31. General relation between permissible cutting speed for a constant tool life and plan angle for a constant area of cut
(*Dempster Smith*)

To summarize, all conditions which involve small values of undeformed chip thickness cause relatively low rates of tool wear. Therefore, a high feed combined with a low depth of cut, or a low feed combined with a high depth of cut, a small plan angle, a large nose radius—all cause relatively low rates of tool wear. The angle in plan between two intersecting cutting edges should be kept as large as possible.

RAKE AND CLEARANCE ANGLES. The effect of rake angle on the durability of high-speed steel tools is shown in Fig. 2.32, from which it is seen that the permissible cutting speed passes through a maximum value. For a given cut, the average chip temperature is lowered as the rake is increased in the positive direction, but at high values of rake. heat conduction is adversely affected by the small wedge angle, and this, together with the mechanical frailty of the cutting edge, appears to outweigh the advantages resulting from the lower energy requirement and the smaller force acting normal to the tool face. With low values of rake, these latter effects seem to be more important than the greater conductivity of the tool. With high-speed steel tools cutting mild steel the least wear seems to occur when the rake angle is between 10 and 20°. The advantage of a negative rake angle used for cemented carbide cutting tools seems to be the strengthened cutting edge which results. The same advantage can be obtained by having a negative rake land followed by a positive rake main face.

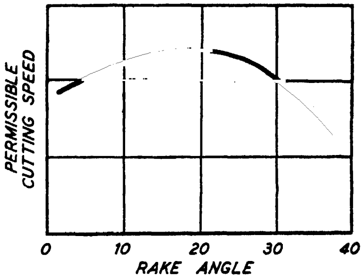

Fig. 2.32. General relation between permissible cutting speed for a constant tool life and rake angle when turning mild steel with high-speed steel tools

(Dempster Smith)

Contrary to traditional practice, which has employed "as small a clearance angle as possible", it has been found that relatively large clearance angles (up to 20°) appreciably reduce the rate of flank wear, and therefore in some cases increase the tool life.

Cutting Fluids. The function of a cutting fluid at high speeds seems to be to increase tool life by cooling, which explains the good properties of plain water as a cutting fluid. A cutting fluid may also increase tool life by lubricating the chip and hence by reducing the severity of the conditions. Methods of applying a high-velocity jet of cutting fluid into the space between the tool flank face and the workpiece seem to be effective in prolonging tool life.

Recommendations for Permissible Cutting Speeds. In the literature there have appeared empirical formulae which were said to enable the permissible cutting speed to be calculated from a number of constants, the values of which had been determined experimentally. A tendency is now growing to believe that these formulae have only limited usefulness. Owing to the large number of variables involved in machining processes, the accuracy of these estimations is not likely to be great. They should therefore be considered as rough guides, and it should be anticipated that experimentation on the shop floor is necessary to obtain optimum conditions for particular jobs. Efficient planning and interpretation of this experimental work requires a knowledge of the general effects of the factors involved, and an understanding of the principles governing the selection of optimum conditions.

THE ECONOMICS OF MACHINING OPERATIONS. Theoretical investigation of machining costs, using the tool-life relationships, shows that in performing an operation on a batch of components variation in the cutting speed, keeping the feed or undeformed chip thickness constant, causes the total cost of machining the batch to pass through a minimum value. The cutting speed and the tool life corresponding to this minimum cost are called the *economical cutting speed* and the *economical tool life* respectively. As the cutting speed is raised the tool and grinding costs increase, but the cost of the actual cutting time diminishes. At the economical speed, an economical balance is made between these two groups of costs.

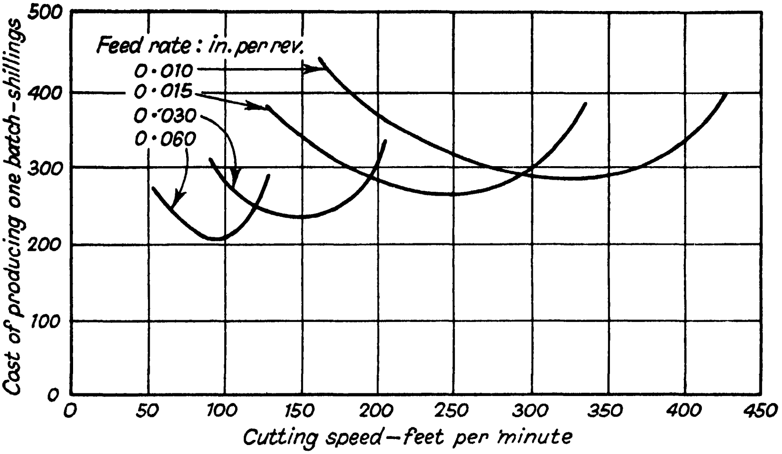

Fig. 2.33.

Further investigation shows that the cost of machining can be diminished still further by increasing the feed (undeformed chip thickness), but the economical cutting speed is then lowered (Fig. 2.33). Thus, at each value of feed, there is a corresponding economical cutting speed, and this falls as the feed rises. The lowest cost is obtained with the highest possible feed. In practice, the feed is limited by one of the following factors:

(*a*) Cutting forces. These affect the elastic deflections under load of tool and workpiece (and therefore may affect the geometric accuracy of machining); they also affect the stresses imposed on the tool, the machine, and the workpiece.

(*b*) Power available for cutting; the power required at the economical speed rises as the feed is increased.

(*c*) Permissible surface roughness.

(*d*) Permissible level of "chatter" vibrations.

In practice, it is important to know how *significant* the economical cutting conditions are; that is, to know what variations in the cutting conditions are permissible in order that the cost of machining a batch does not rise by more than a definite amount above the minimum cost. The significance of the economical conditions varies with different types of operations, and trial estimates in a few cases will show the relative importance of the economical cutting conditions in different classes of work. Nomographs which present the tool-life relationships such as developed by Gilbert and Truckenmiller* facilitate this work.

For Bibliography see end of book.

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* Gilbert, W. W., and Truckenmiller, W. C., *Mech. Eng.* (1943), **65**, 893.

CHAPTER III

TURNING

By DR. F. KOENIGSBERGER

The Turning Process. In this process the workpiece rotates round a fixed axis, that of the spindle bearings (A), the shape and size of the product being determined by the track of the tool, which is clamped on the tool rest (B), during its feed movement. This can take place parallel to the axis of rotation by means of saddle (C) and transversely by means of cross-slide (D) (Fig. 3.1), which also serves for the diametral setting of the cutting edge. For certain operations the setting or feed movement can also be effected by traversing the tool rest slide (F).

The mechanism of chip removal during turning has been described in detail in Chapter II.

THE CUTTING FORCE. The cutting force P can be divided into three components in the following directions (Fig. 3.2).

1. Tangential to the machined surface and at a right angle to its axis. This component (P_1) determines, together with the cutting speed (v), the net power required at the cutting edge and provided by the spindle drive.
2. Radial to the machined surface in the direction of the depth setting, i.e. in line with the cross-slide traverse (D, Fig. 3.1). This component (P_2) may cause deformations which affect directly the accuracy of the finished workpiece.
3. Parallel to the axis of rotation of the workpiece, i.e. in the direction of the feed movement. This component (P_3) determines, together with the feed velocity, the net power required from the feed drive.

Factors which affect the magnitudes of the cutting force and its components and the effects of cutting speed and feed rate on the performance of the tools have been discussed in Chapter II.

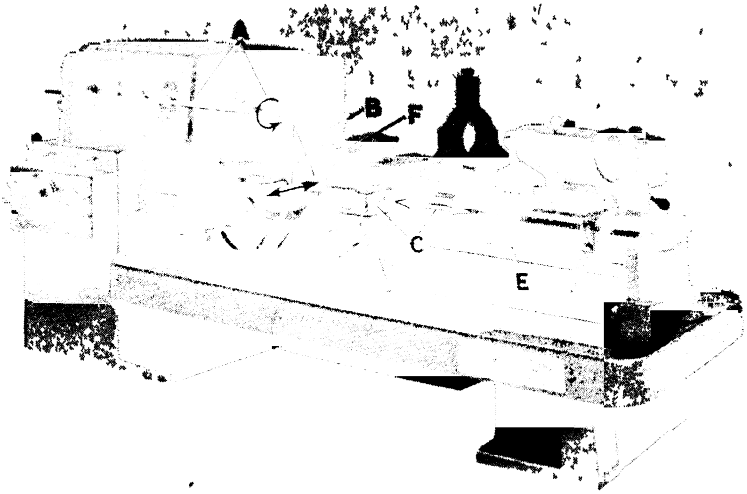


Fig. 3.1. C.V.A.-Lodge & Shipley "Powerturn" tool-room lathe
(C.V.A. Jigs, Moulds & Tools Ltd., Hove, Sussex)

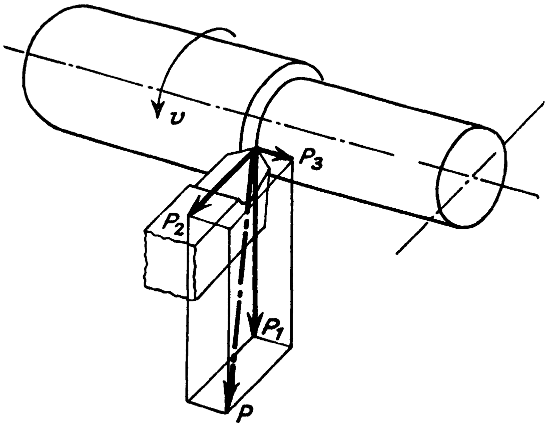


Fig. 3.2

Although under different cutting conditions the magnitude of the specific cutting resistance k_s varies considerably even for the same workpiece material, the German Committee for Economic Production (AWF) have published values (AWF 158) which can be taken as a guide for the determination of machine capacities and power requirements. These mean values (Fig. 3.3) obtainable with tools and machines conforming with good average workshop practice are valid between ratios of $a/s = 2$ and $a/s = 10$, where a is the depth of cut, and s the feed rate per revolution of the workpiece. With these values the three cutting force components can be determined as follows:

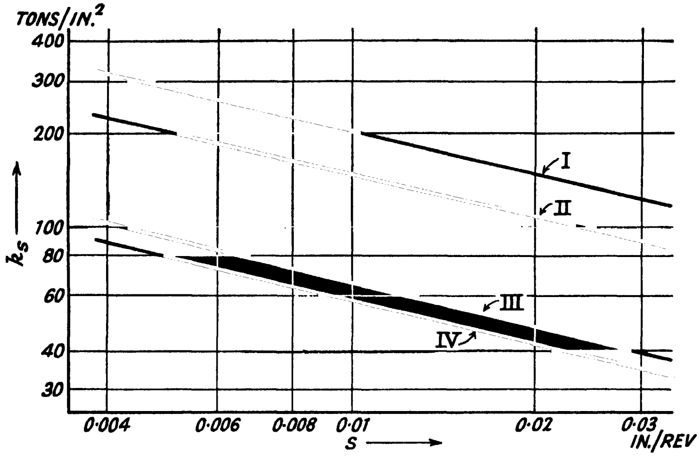


Fig. 3.3

I, Alloy steel up to 65 tons/in²
II, Carbon steel up to 32 tons/in²
III, Brass
IV, Aluminium

$$P_1 = a.s.k_s$$
$$P_2 \simeq 0{\cdot}3\ P_1$$
$$P_3 \simeq 0{\cdot}15 \text{ to } 0{\cdot}5\ P_1$$

CUTTING SPEED. The selection of an optimum cutting speed depends upon the requirements and conditions of the workpiece, on the characteristics of the machine, and on the type, shape and material of the tool.

As a general guide, however, values can be established for cutting various materials with high-speed steel and tungsten carbide tools. These values are related to the required or expected tool life, and this has been specified in accordance with the following recommendations:

(*a*) *Centre lathe work*
High-speed steel tools—60 minutes.
Tungsten carbide tools—240 minutes.

(*b*) *Capstan, turret or automatic lathe work*
240 or 480 minutes.

Fig. 3.4 shows recommended cutting speeds (AWF 158) plotted against the feed rates per revolution. The speeds are valid for depths of cut up to 0·2 inch and for a plan angle of 45°. For greater depth and larger angles the cutting speed values have to be reduced.

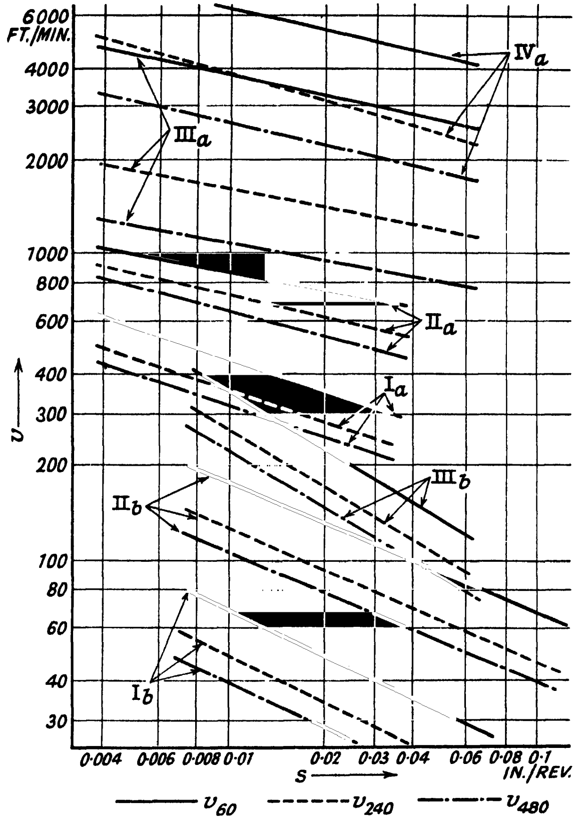


Fig. 3.4

(*a*) Tungsten carbide tool. (*b*) High-speed steel tool

I, Alloy steel up to 65 tons/in^2

II, Carbon steel up to 32 tons/in^2

III, Brass

IV, Aluminium

With a knowledge of the cutting force (P_1 in lb.) and the cutting speed (v in feet/minute) the net horsepower required at the cutting edge can be calculated as

$$\text{h.p.} = \frac{P_1 \,.\, v}{33{,}000}$$

FEED. The feed rate is generally chosen in accordance with the other cutting conditions and the surface finish requirements (see Chapter II).

Turning Operations. The track of the tool edge can be (Fig. 3.5):

(*a*) Straight and parallel to the axis of rotation, for the production of external (a_1) and internal (a_2) cylindrical surfaces (turning and boring with the saddle C, Fig. 3.1, driven by rack and pinion).

(*b*) Straight and at right angles to the axis of rotation (surfacing with the cross-slide D, Fig. 3.1).

(*c*) Straight and inclined to the axis of rotation (taper turning, e.g. by combination of movements C and D, Fig. 3.1).

(*d*) Straight and parallel to the axis of rotation at a highly accurate feed rate relative to the rotation of the workpiece (screwcutting with the saddle C driven by lead screw E, Fig. 3.1).

(*e*) Circular around a vertical axis which lies at right angles to the axis of rotation (by means of a specific fixture) for the production of spheres.

(*f*) Following any desired path by means of a special device, e.g. a template which controls the movement of the cross-slide (D, Fig. 3.1) in relation to the normal longitudinal movement of the saddle (C, Fig. 3.1) (profile copy turning).

(*g*) and (*h*) Workpieces of non-circular section can be produced if the transverse movement (D, Fig. 3.1) of the tool holder is controlled appropriately as in the machining of ingots (*g*) and for relieving, e.g. in the production of milling cutters (*h*).

Some of these operations will now be discussed in more detail.

1. TURNING AND SURFACING. The cutting speed v depends upon the diameter d to be turned and the number of revolutions per minute n of the workpiece.

$$v = \pi dn$$

The spindle speed n is chosen in such a manner that the circumferential velocity at the diameter d to be machined does not exceed the maximum cutting speed v which is permissible under the prevailing conditions (see Chapter I).

Cylindrical turning. The time t for turning a cylindrical surface of length l depends on the feed rate s (inches per revolution of the spindle) and the spindle speed n (r.p.m.).

$$t = \frac{l}{n \, . \, s}$$

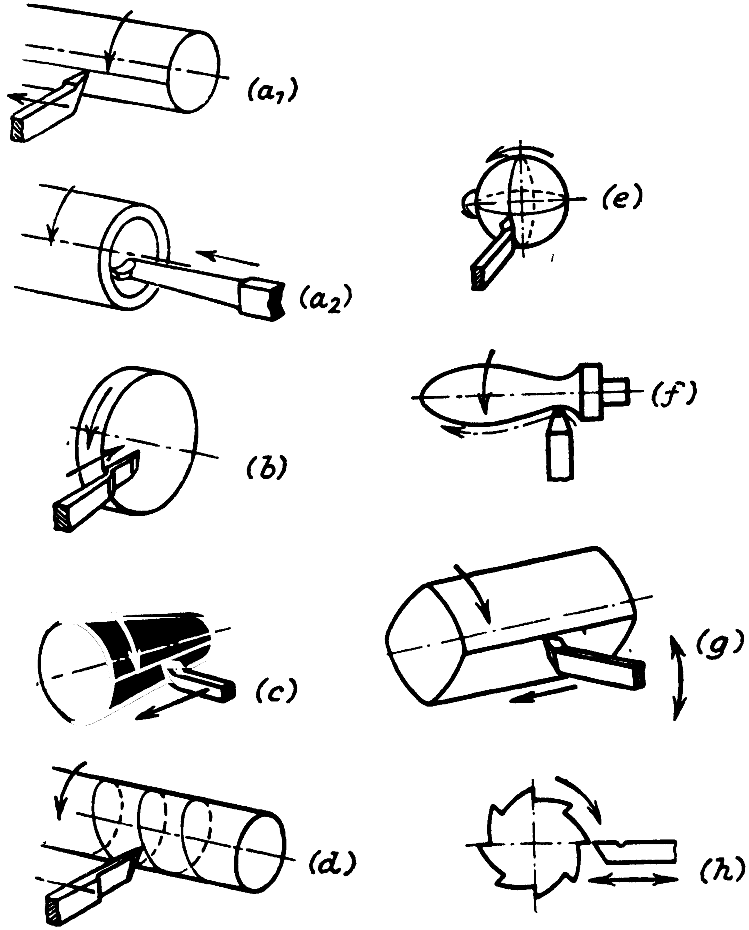


Fig. 3.5

Surfacing. If the spindle speed is to be kept constant during a surfacing operation the circumferential velocity of the maximum diameter $d_{\max}$ to be machined (Fig. 3.6) determines the spindle speed. With the diameter steadily decreasing during the operation the cutting speed drops more and more below its optimum value. This may not only affect the quality of the operation, but will also result in uneconomical machining times.

Various devices have been developed for infinitely varying the spindle speed in accordance with the instantaneous cutting diameter during the surfacing operation, in order to maintain the circumferential velocity—the cutting speed—at its optimum value. The saving in machining time which can be obtained may be considerable. For the case of surfacing at a constant spindle speed from a maximum diameter $d_{\max}$ down to a minimum diameter $d_{\min}$ at a feed rate s and a permissible cutting speed v (Fig. 3.6) the machining time t_1 is

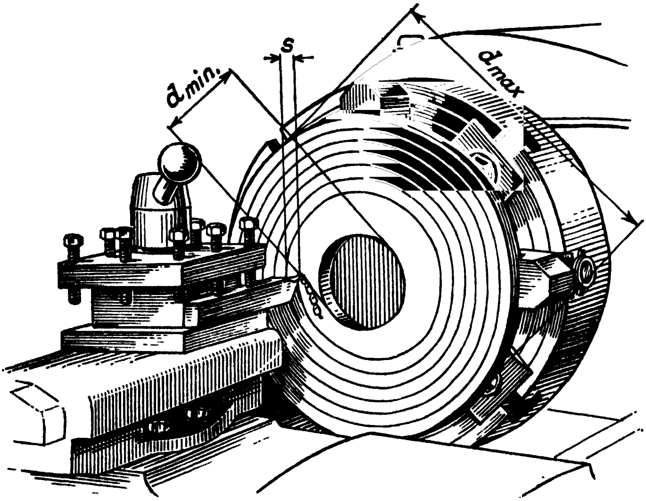


Fig. 3.6. Surfacing

$$t_1 = \frac{\dfrac{d_{\max} - d_{\min}}{2}}{\dfrac{v}{\pi d_{\max}} \cdot s} = \frac{(d_{\max} - d_{\min})\,\pi d_{\max}}{2\,v\,s}$$

If, by means of an infinitely variable speed drive and suitable controls, the spindle speed can be gradually increased so as to keep the cutting velocity constant during the whole operation, the machining time can be determined by assuming that

$$N = \frac{d_{\max} - d_{\min}}{2\,s}$$

circular rings have to be turned with a mean circumference of

$$\pi \cdot \frac{d_{\max} + d_{\min}}{2}$$

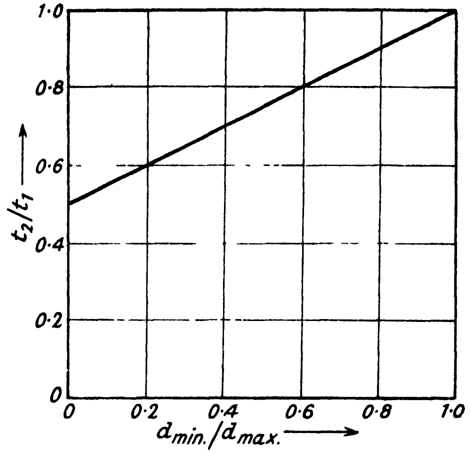


Fig. 3.7*a*

At a constant circumferential velocity v the time per ring will be

$$t' = \frac{\pi \dfrac{d_{\max} + d_{\min}}{2}}{v} = \frac{\pi}{2v}(d_{\max} + d_{\min})$$

and the total time for N rings to be turned becomes

$$\begin{aligned} t_2 &= N . t' \\ &= \frac{\pi (d_{\max} + d_{\min})(d_{\max} - d_{\min})}{2v . 2s} \\ &= \frac{\pi (d_{\max} + d_{\min})(d_{\max} - d_{\min})}{4vs} \end{aligned}$$

The increase in productivity can be judged from the ratio of the two times:

$$\frac{t_2}{t_1} = \frac{d_{\max} + d_{\min}}{2d_{\max}} = \tfrac{1}{2}\left(1 + \frac{d_{\min}}{d_{\max}}\right)$$

Although theoretically a 50 per cent time-saving is possible if $d_{\min} = 0$, that is, if a complete circular face is machined, this cannot be achieved in practice, as for $d_{\min} = 0$ the spindle speed ought to approach infinity. The graph (Fig. 3.7*a*) is, therefore, valid only down to those values of $d_{\min}$ for which the maximum spindle speed $n_{\max}$ available on the lathe allows the optimum circumferential velocity v to be obtained, i.e.

$$d_{\min} = \frac{v}{\pi n_{\max}}$$

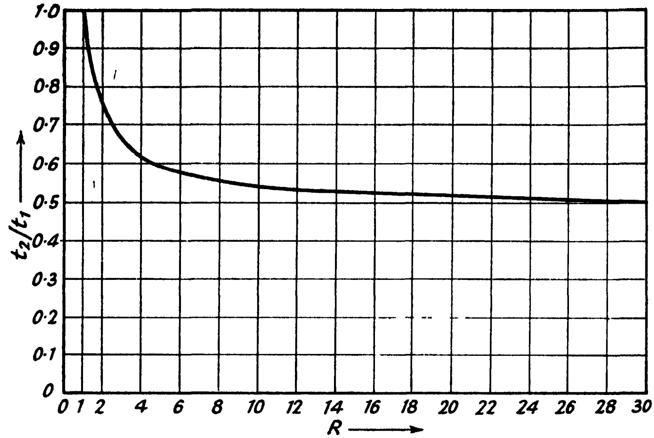


Fig. 3.7*b*

As the maximum diameter which can be turned depends similarly on the minimum available spindle speed $n_{\min}$ the maximum saving, i.e. the minimum ratio t_2/t_1 obtainable on a particular lathe is

$$\left(\frac{t_2}{t_1}\right)_{\min} = \frac{1}{2}\left(1 + \frac{n_{\min}}{n_{\max}}\right)$$

The ratio $R = \dfrac{n_{\max}}{n_{\min}}$ indicates the speed range provided by the spindle drive (see Chapter 1), so that

$$\left(\frac{t_2}{t_1}\right)_{\min} = \frac{1}{2}\left(1+\frac{1}{R}\right) \text{ (Fig. 3.7b).}$$

2. Taper Turning.* Tapers can be turned by one of four well-known methods:

(*a*) form tool;
(*b*) swivelled tool rest (upper slide);
(*c*) off-set tailstock;
(*d*) taper attachment.

---

* See M. M. Barash, "On the Turning of Tapers", Bulletin of Mechanical Engineering Education, the Manchester College of Science and Technology, No. 13, January 1958.

The first method is suitable only for very short tapers. The other three methods have the fact in common that the taper is generated by the straight-line movement of a single-point tool.

The swivelled upper slide (F, Fig. 3.1) makes possible the turning of relatively short tapers of any angle, internal as well as external. Manual feed is usually employed. Thread-cutting with this method is not usually possible except with certain instrument-makers' lathes which are provided with a universal joint drive for the upper slide.

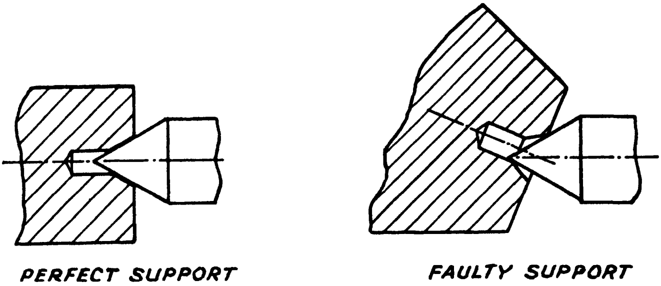


Fig. 3.8

The off-set tailstock method is unfortunately still used in spite of its several serious shortcomings which are not always realized. The attraction in using this method lies apparently in the fact that the length of the taper is limited only by the length of the lathe. The disadvantages are, however, serious.

Even from the point of view of workshop efficiency it is questionable whether it is wise to upset the tailstock. It is a tedious procedure to return the tail stock accurately to its previous position for parallel turning, and this would have to be repeated after each offset. The setting operation could be checked only by taking actual trial cuts, as attempts to design locating means for resetting have not met with success.

Lathe centres and centre holes are standardized. Perfect support of the workpiece on centres can be achieved only if the axes of the centres and of the workpiece coincide. This condition cannot be met in turning with an offset tailstock and consequently the support will be impaired (Fig. 3.8). The centre hole may even be damaged, and this will result in difficulties if the taper has to be held between centres for subsequent operations such as grinding. Special shapes of the centres have been suggested (Fig. 3.9) and spherical centres (Fig. 3.10) have been used, but even in these cases

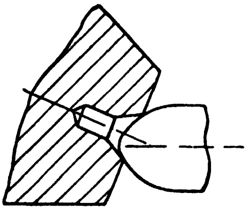


Fig. 3.9

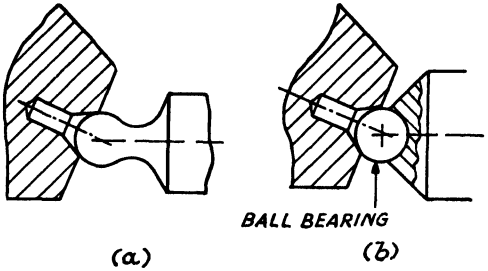


Fig. 3.10

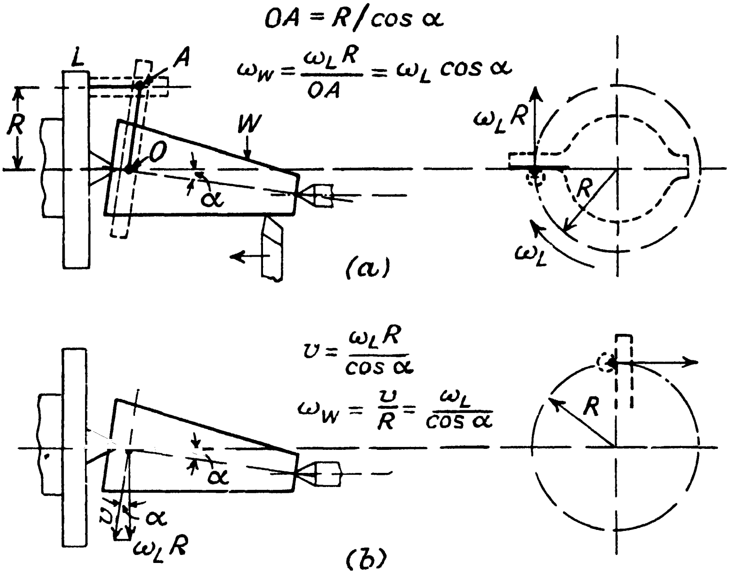

$OA = R/\cos\alpha$
$\omega_W = \frac{\omega_L R}{OA} = \omega_L \cos\alpha$
L
A
R
W
O
α
$\omega_L R$
R
ω_L
(a)
$v = \frac{\omega_L R}{\cos\alpha}$
$\omega_W = \frac{v}{R} = \frac{\omega_L}{\cos\alpha}$
α
v
α
$\omega_L R$
R
(b)

Fig. 3.11

line contact and not surface contact is obtained, and the centres may not be able to withstand roughing cuts and will wear out of shape.

When the offset tailstock method is used for making a taper thread, the lathe being geared to produce n threads per inch, the actual pitch of the taper thread, measured on its side, will be $n/\cos\alpha$. If a taper (included angle 2α) is to be machined with the usual one-sided carrier as shown in Fig. 3.11 the angular velocity ω_W of the taper will be $\omega_W = \omega_L \cos\alpha$ when the driving pin is in the plane of the taper axis, i.e. in the horizontal plane of the lathe as shown in Fig. 3.11*a* (ω_L is the angular velocity of the spindle). After the spindle has rotated 90° and the driving pin is just above the centre (Fig. 3.11*b*) the angular velocity of the taper will be

$$\omega_W = \frac{\omega_L}{\cos\alpha}$$

Due to this variation in the angular velocity of the workpiece the pitch of the thread produced will fluctuate between the values $n/\cos\alpha$ and $n \cos\alpha$. The result is a so-called "drunken thread".

The best method of turning tapers, using power traverse, is by means of a taper attachment (Fig. 3.12), in which the transverse cross-slide position is controlled during the longitudinal saddle movement in accordance with the required taper angle to which the guiding device is set. The only limitations of this method are the angle (up to about 20° due to friction) and the length of the taper that

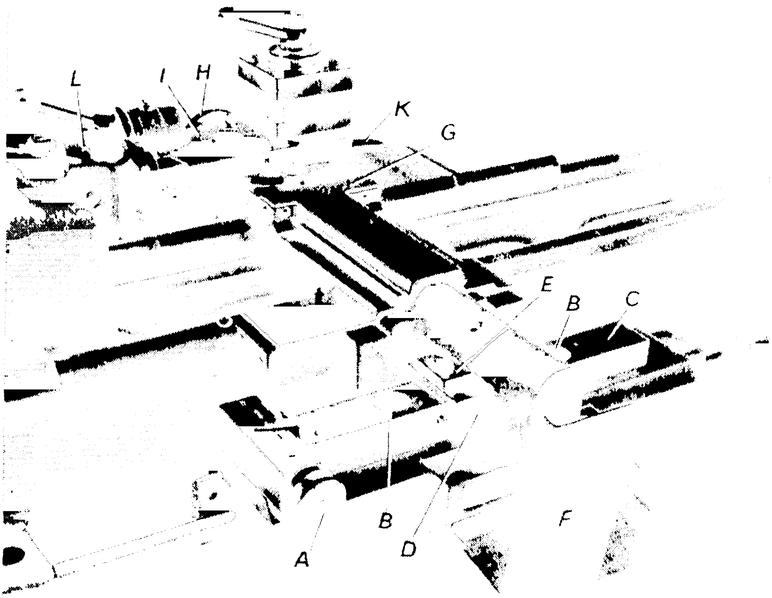


Fig. 3.12. Taper turning attachment

A, Angular adjustment of taper guide bar. *B*, Clamping taper guide bar in selected angle position. *C*, Taper guide bar. *D*, Taper guiding block. *E*, Block carrying thrust bearings for cross traverse screw. *F*, Hinged cover. *G*, Cross slide. *H*, Cross traverse hand wheel. *I*, Tool rest slide. *K*, Longitudinal traverse hand wheel. *L*, Tailstock.

(*Dean, Smith & Grace Ltd., Keighley*)

can be turned. The lathe centres remain in their correct position and none of the before-mentioned disadvantages of the offset tailstock method is encountered.

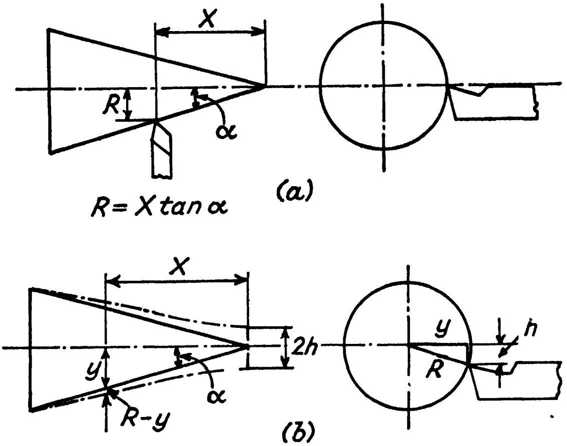


Fig. 3.13

An important point to be considered in connection with taper turning is the setting of the tool above or below the centre. When the tool is set at the correct centre height the radius of the taper is $R = x \,.\, \tan\alpha$ (Fig. 3.13*a*). If the tool is lowered or raised by an amount h the radius produced at any point is

$$R^2 = y^2 + h^2$$

As the movement of the tool is governed by the equation

$$y = x \,.\, \tan\alpha$$

the relationship between the radius and the length of the taper becomes

$$\frac{R^2}{h^2} - \frac{x^2}{h^2/\tan^2\alpha} = 1$$

which means that the taper distorts more and more into a hyperboloid of revolution the greater the error in the centre height setting of the tool. It may be mentioned in this connection that this error results also in a variation of the cutting and clearance rakes. This applies of course to any turning operation, but in view of the variation increasing with decreasing diameter it may become considerable at the smaller end of a taper in the cases of taper turning.

3. SCREW-CUTTING. For the cutting of accurate screw threads the lead screw provides the longitudinal feed drive for the saddle.

If a certain pitch p_W of a single-start screw thread (or a lead of the same value in case of a multi-start screw thread) has to be cut, in other words, if the tool has to travel longitudinally by an amount p_W during each revolution of the spindle, and if the pitch of a single-start (or the lead of a multi-start) lead screw is p_s (in./turn), the speed ratio between spindle and lead screw must be

$$r = \frac{p_W}{p_s}$$

This can be produced by means of change gears between spindle and lead screw drive. On many lathes, however, the ratios required for the production of most standard screw threads are obtainable from a feed drive gear-box, frequently of the Norton type (see Chapter I).

When metric threads have to be cut with an inch lead screw or vice versa a special "conversion gear wheel" is often provided. As one inch is equal to 25·4 mm. with considerable accuracy, a conversion gear with 5 × 25·4 = 127 teeth enables screw threads of the required accuracy to be produced.

As an example, for cutting a single-start screw thread of 5 mm. pitch with a single-start lead screw of ½-inch pitch the tool must travel 5 mm. = 5/25·4 inches per revolution of the spindle. The speed ratio between spindle and lead screw is therefore

$$r = \frac{5}{25{\cdot}4} \bigg/ \frac{1}{2} = \frac{5 \times 2}{25{\cdot}4} = \frac{50}{127}$$

4. PROFILE TURNING. Similar to the guiding of the cross-slide during the longitudinal movement of the saddle, in the case of taper turning the cross-slide position can be controlled by templates in accordance with any profile which has to be produced. As the forces involved are often considerable, especially in roughing cuts, and excessive pressure on the template would result in undesirable wear, a servo-mechanism (hydraulic or electric) is often inserted between the template and the cross-slide positioning device. An example of a hydraulic device in which the template operates a hydraulic valve which, in turn, controls the cross-slide positioning

device (hydraulic cylinder and piston) is shown in Fig. 3.14. One of the best-known machines incorporating this principle and specially designed for profile turning is the profiling lathe, Fig. 3.15. Recent developments have led to the design of electronic servo-

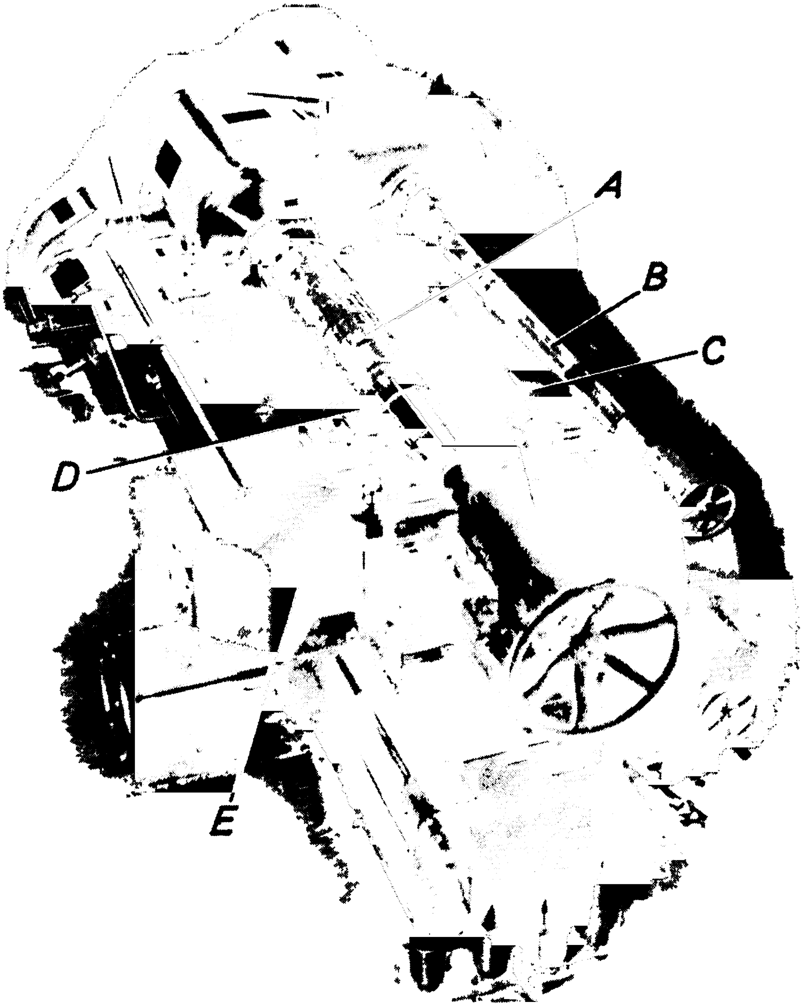


Fig. 3.14. Hydraulic copying device for a centre lathe
A, Workpiece to be machined *B*, Turned workpiece used as template *C*, Tracer *D*, Turning tool. *E*, Copying slide

(*Metropolitan-Vickers Electrical Co. Ltd., Manchester*)

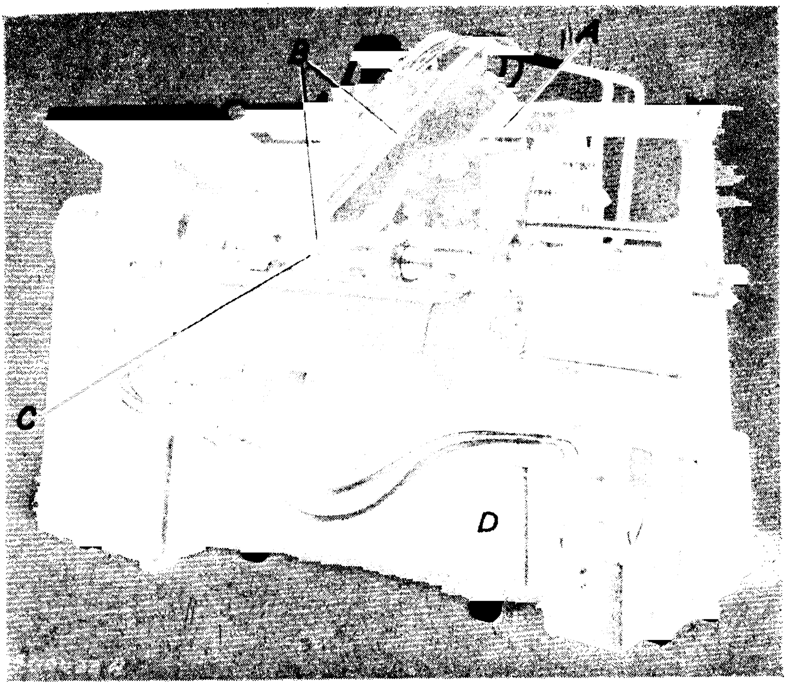


Fig. 3.15. Automatic copying lathe

A, Master or template. *B*, Hydraulically operated tool slide turning tool. *C*, Work piece. *D*, Removable swarf tray.

(*G. Fischer, Schaffhausen, Switzerland*)

controls in which the profile is controlled by information taken from a magnetic tape.

5. NON-CIRCULAR TURNING. For the purpose of non-circular turning (items (g) and (h), Fig. 3.5), the cross-slide position is controlled by cams or lever arrangements in such a manner as to produce the required strokes per revolution of the workpiece.

Vertical Boring Machines. When heavy and cumbersome workpieces have to be machined, especially pieces of large diameter and relatively short length, machines with a vertical turning axis have been found advantageous, because the workpieces can be lifted relatively easily on to the table which represents a horizontal faceplate or chuck (A, Fig. 3.16). The obtainable accuracy is also good because the weight acts parallel to the axis of rotation, and radial deflections of the spindle in its bearings are small. On the machine

(Fig. 3.16) the tool-carrying turret head (B) is located on a swivelling vertical slide (C), which, is in turn, carried on a cross-traversing saddle (D).

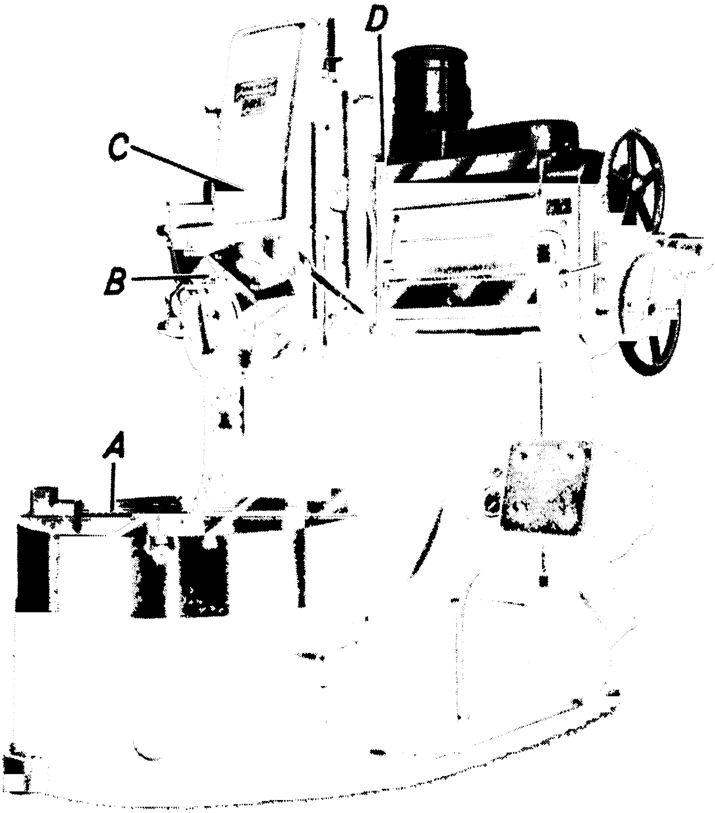


Fig. 3.16. Vertical boring machine

(*Webster & Bennett, Coventry*)

Capstan, Turret and Automatic Lathes. When a sequence of different operations has to be carried out on a centre lathe the operator must set his tools each time he changes from one operation to the next. This becomes lengthy and expensive in the case of repetition work. When large quantities of identical components have to be produced, the time for setting the tools for each operation has to be spent over and over again for each component of the batch to be machined, and the operator's skill has to be repeatedly applied for each of these tool-setting operations. A natural development in line with the requirements of larger-quantity production was to pre-set on a swivelling head a particular tool or set of tools for each operational step. Each tool can thus be swung into its operational position without any particular skill on the part of the operator. In the combination turret lathe (Fig. 3.17) each set of tools allocated to operations 1 to 6 is held by a special tool holder (A), and these tool holders in turn are each fastened to one of the six faces of the hexagon turret head (B). As an example, operation 1 shows a boring tool and two external turning tools set to operate at two different diameters. The turret is located on a longitudinally travelling saddle (C). A second saddle (D) carries a cross-slide (E) with a square turret head (F) for facing and grooving tools and a rear tool holder (G) for parting-off operations.

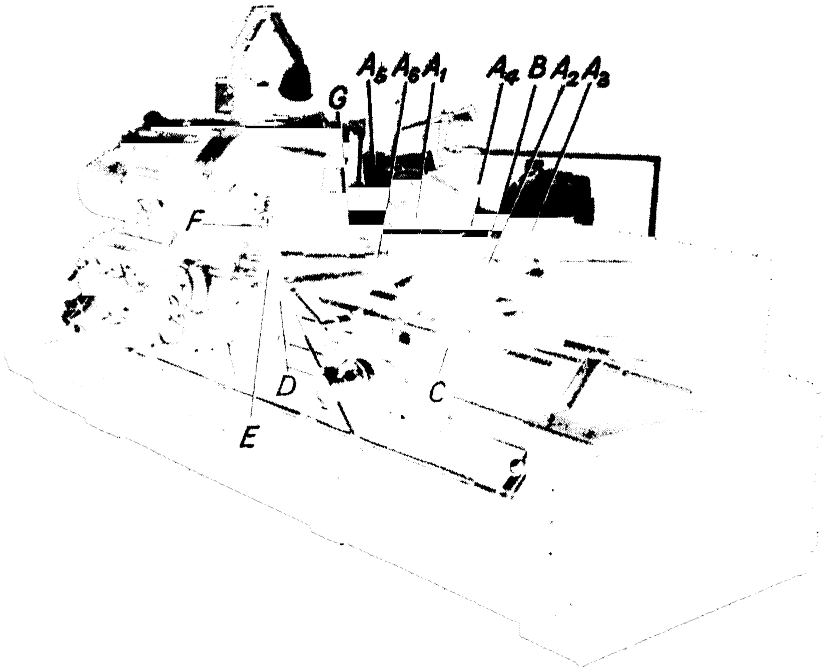


Fig. 3.17. Combination turret lathe
(*Alfred Herbert, Coventry*)

On smaller machines the working stroke, operated by a cross-handle, need not cover the full length of the machine bed. The saddle (A) of the capstan lathe (Fig. 3.18) can be clamped anywhere on the bed slides, and the longitudinal feed movements are allocated to a small slide (B) which carries the turret head (C).

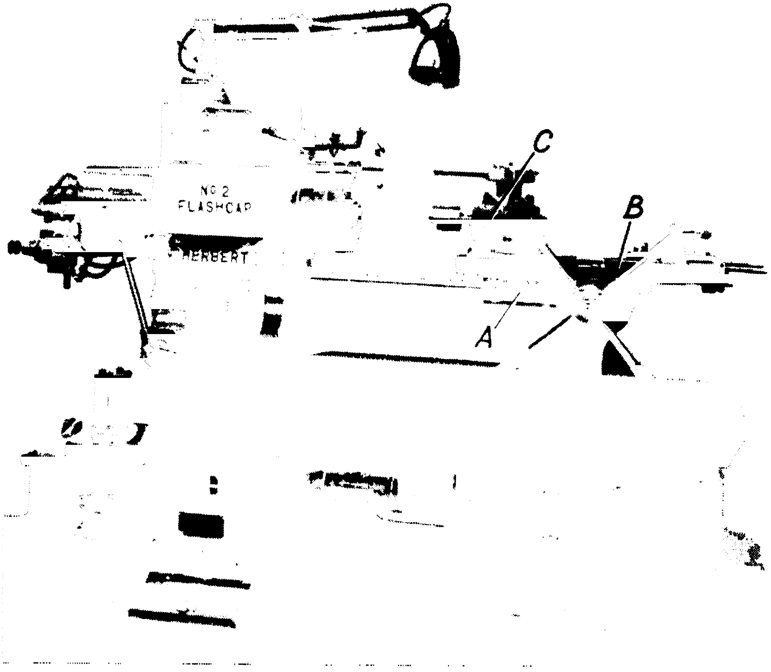


Fig. 3.18. Capstan lathe

(*Alfred Herbert*, *Coventry*)

The workpiece material for these machines can be supplied either in the form of single components (castings, forgings, etc.) which are normally held in chucks (mechanically, hydraulically or pneumatically operated) or in the form of long bars which are held by collets. The front of the collets is usually split into three segments (Fig. 3.19*a*) and for clamping they are closed by the action of a taper. If the clamping is caused by axial movement of the collet itself, by either pushing or pulling (Figs. 3.19*b*–*c*), the bar material will be either pushed forward or pulled back during the closing of the collet, and longitudinal accuracy is difficult to maintain. If the collet is prevented from axial movement (Fig. 3.19*d*) and closed by the movement of an external tubular locking taper this difficulty does not arise.

A considerable amount of special tooling equipment has been

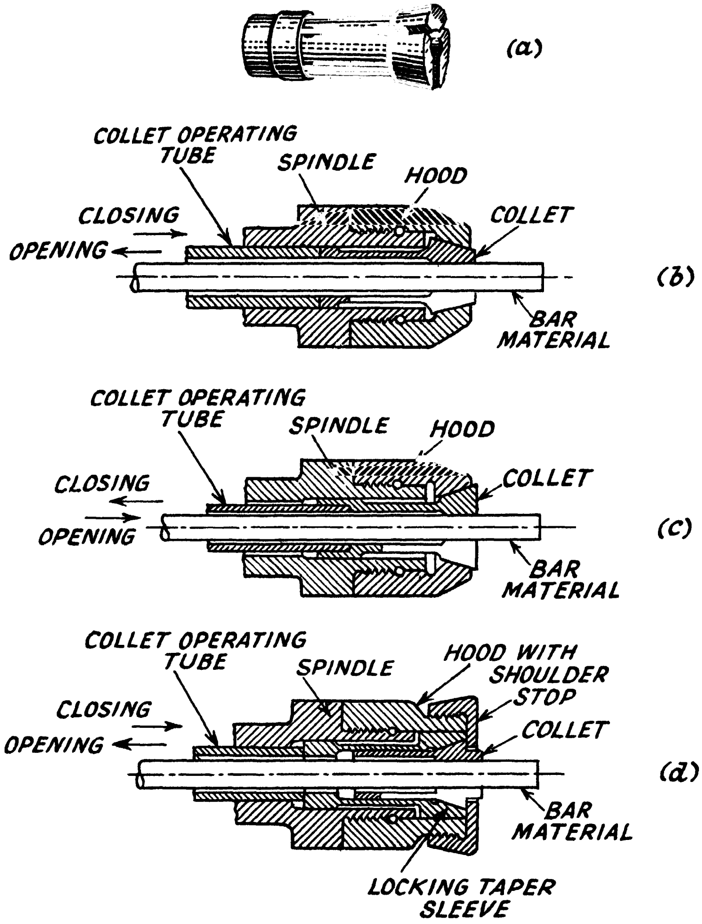


Fig. 3.19

developed for ease of operation of capstan and turret lathes by unskilled labour. Mention may be made of roller boxes in which sets of rollers support the workpiece against the deflecting action of the cutting force, screw-cutting die heads with collapsible dies which make it unnecessary to reverse the spindle for unscrewing the die head from the finished thread, etc.

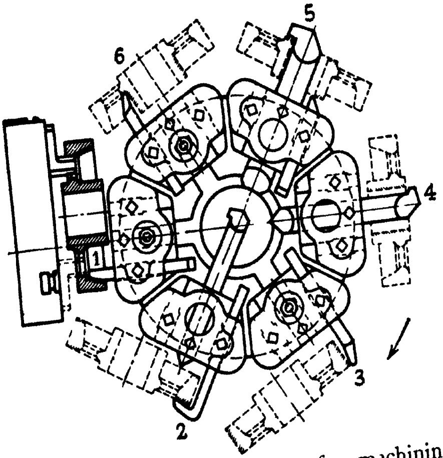


Fig. 3.20. Operation layout for machining a pulley on a turret lathe

1, Turning inside of rim. 2, Facing both sides of rim. 3, External turning of rim. 4, Boring. 5, Facing both sides of hub. 6, Turning of hub

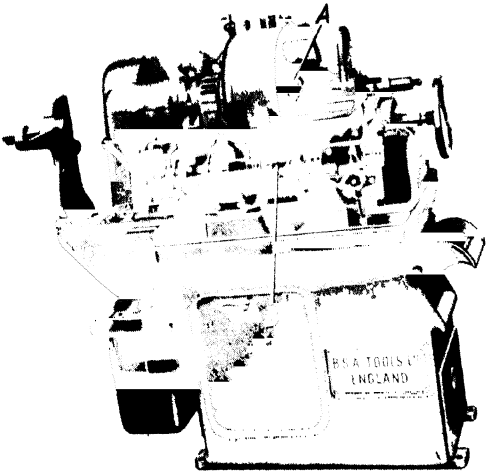


Fig. 3.21. Single-spindle automatic
(*B.S.A. Tools Ltd., Birmingham*)

A typical operational layout showing the tooling arrangement for machining a pulley is shown in Fig. 3.20.

From hand operation by an unskilled operator it is but one step to the operation of the various tool holders by means of cams as used in automatic lathes.

Fig. 3.21 shows a single-spindle automatic with a turret head (A) and a master camshaft (B).

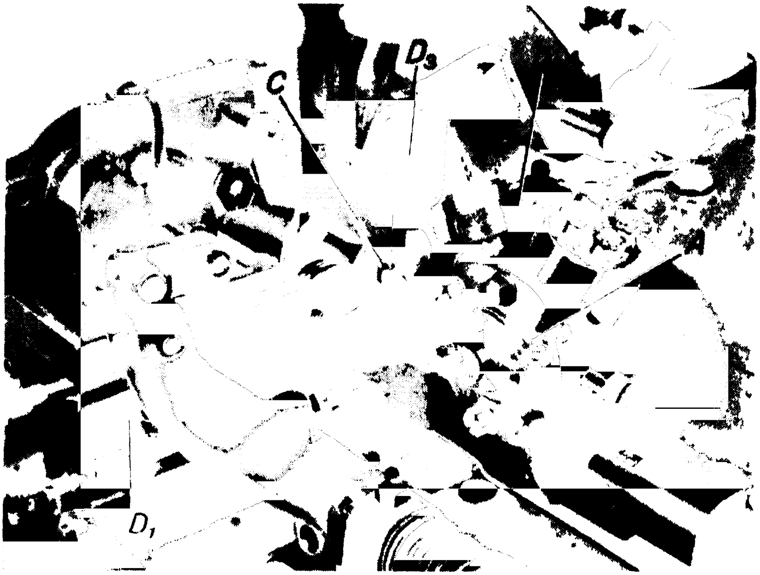


Fig. 3.22. Tool layout of automatic shown in Fig. 3.21

Fig. 3.22 shows the tool layout of the same machine. The turret head (A) and the split collet (C) can be clearly seen.

These machines have usually two or three cross-slides (D_1, D_2, D_3) for grooving, form turning and cutting-off operations.

A typical layout for turning a small component on a single-spindle automatic is shown in Fig. 3.23 and the cam layout is shown in Fig. 3.24.

Multi-spindle automatic machines have also been developed in which several components (four to six) are machined simultaneously, each spindle carrying a bar of material or a component in a chuck. Facing each spindle is one of the tool sets, so that operations

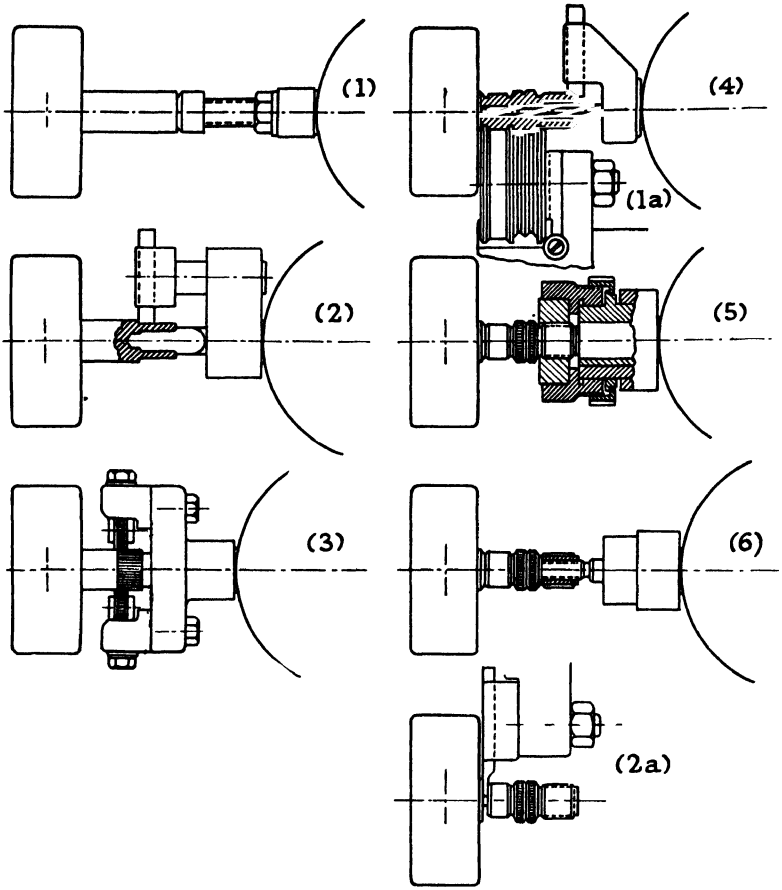


Fig. 3.23. Plan of operations for single-spindle automatic

1, Material feed against stop. 2, Drilling and turning for screw cutting. 3, Knurling. 4, Drilling and chamfering. 5, Cutting of external thread. 6, Cutting of internal thread. 1a, Profile turning with front cross slide (simultaneous with Op. No. 4). 2a, Parting off with rear cross slide

1 to 4, or 1 to 6, are simultaneously executed, one on each component. After each operational stroke of the tool slide the spindle head is switched round (a quarter of a turn in the case of four-spindle automatics, one-sixth of a turn in the case of six-spindle automatics) so that each component faces the tools for the subsequent operation.

When the first workpiece has completed its full cycle and is parted off or released, one completed component is produced after

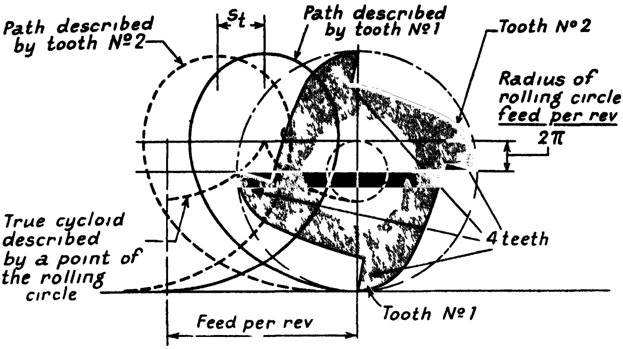

Path described by tooth Nº2
s_t
Path described by tooth Nº1
Tooth Nº2
Radius of rolling circle $= \frac{\text{feed per rev}}{2\pi}$
True cycloid described by a point of the rolling circle
4 teeth
Tooth Nº1
Feed per rev

Fig. 4.1

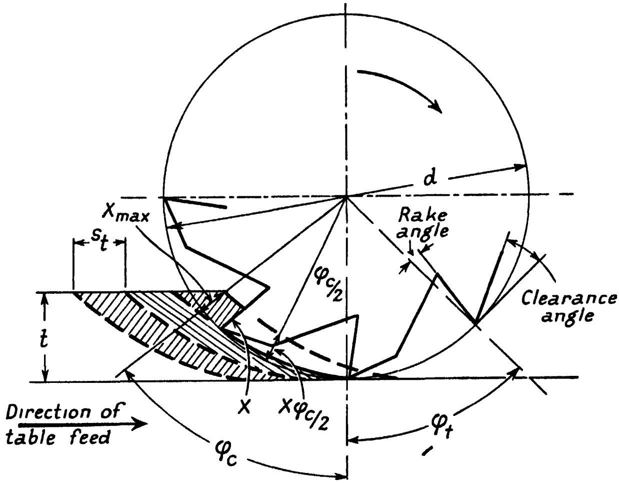


Fig. 4.2

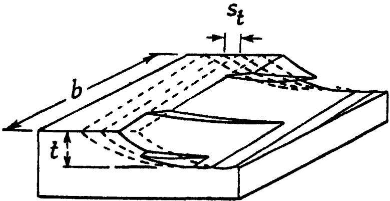


Fig. 4.3

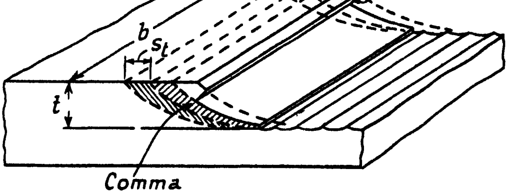


Fig. 4.4

the teeth ($\varphi_t = \frac{360}{n_t}$, see Fig. 4.2) where n_t is the number of teeth of the cutter. The angle of rotation of the cutter during which each tooth remains engaged in the workpiece material depends upon the cutter diameter d and the depth of cut t.

$$\cos \varphi_c = \frac{\frac{d}{2} - t}{\frac{d}{2}} = 1 - \frac{2t}{d} \text{ (see Fig. 4.2).}$$

Although the chip section, and with it the cutting resistance, rises to a maximum and drops sharply as a straight tooth leaves the material, the maximum may be maintained as the cutting action travels, as it were, parallel to the axis of a helical cutter and across the workpiece material (see Fig. 4.3). With the helical cutter, the cutting force/angle of rotation relationship takes the form shown in Figs. 4.5 and 4.6*a*, in which the total resulting force cutting at the cutting edges can be divided into an alternating component superimposed on a steady component. It is also possible to choose the cutting conditions in such a manner that the resulting total cutting force is practically constant (Fig. 4.6*b*).

The foregoing shows that the loading conditions in the milling machine do not depend only on the width and depth of cut but also on the size and type of cutter used and on the spindle speed and table feed chosen for a particular operation.

The actual cutting resistance is influenced by the properties of the workpiece material and by the cutting angles of the milling cutter, the width and depth of cut, the rate of feed (per tooth and per revolution of the cutter) and the cutter diameter.

The chip thickness x (see Fig. 4.2) at any moment is

$$x = s_t \,.\, \sin \varphi$$

where s_t = feed per tooth

and φ = angle of rotation of the cutter.

If the cutter rotates at n rev./min. the feed rate per min. is

$$s = n \,.\, n_t \,.\, s_t$$

and

$$x = \frac{s}{n \,.\, n_t} \,.\, \sin \varphi$$

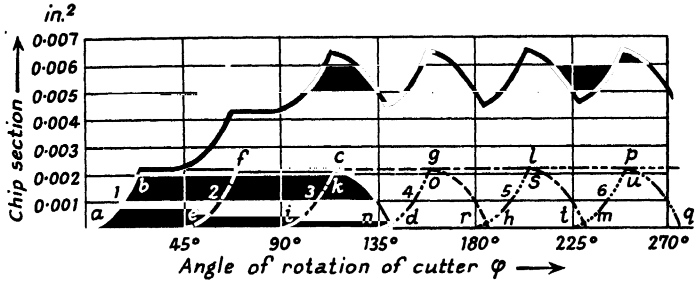
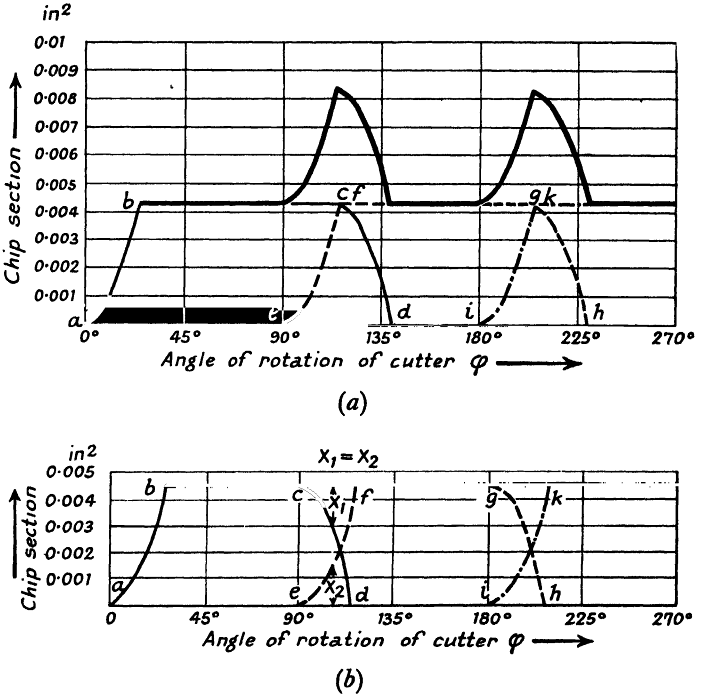


Fig. 4.5. Chip section taken by helical cutter with eight teeth

—— Total chip section

abcd first tooth *efgh* second tooth *iklm* third tooth
nopq fourth tooth *rs* fifth tooth *tu* sixth tooth



(*a*)

(*b*)

Fig. 4.6. Chip sections taken by helical cutters with four teeth

—— Total chip sections

abcd first tooth *efgh* second tooth *ik* third tooth

DATA FOR FIGURES 4.5 and 4.6.

Cutter diameter 4 in. Helix angle 45°. Cutting velocity 65ft./min.
Feed rate 4in./min. Depth of cut 0.2 in. Width of cut 4 in.

$$x_{max} = \frac{s}{n \,.\, n_t} \,.\, \sin \varphi_c \text{ (see Fig. 4.2)}$$

and with
$$\sin \varphi_c = \frac{2\sqrt{t\,(d - t)}}{d}$$

$$x_{max} = \frac{2s\sqrt{t\,(d - t)}}{d \,.\, n \,.\, n_t}$$

The specific cutting resistance varies, however, with the chip section and, therefore, in a straight cut, with the chip thickness *x*. For the purpose of determining the net cutting power a satisfactory approximation can be obtained by finding the specific cutting resistance for the chip thickness at half the angle of rotation of the cutter between entry of a tooth into the material and maximum chip thickness, i.e.

when
$$\varphi = \frac{\varphi_c}{2}, \text{ then } x_{\frac{\varphi_c}{2}} = \frac{s}{n \,.\, n_t} \,.\, \sqrt{\frac{t}{d}} \quad (*)$$

Typical relationships between specific cutting resistance *k* and $x_{\frac{\varphi_c}{2}}$, found from a large number of milling experiments, are shown in Fig. 4.7.

The net power is then determined by multiplying the horse-power per tooth HP_t by the number of teeth n_t

$$\begin{aligned} \text{h.p.} &= HP_t \,.\, n_t \\ &= k \,.\, t \,.\, b \,.\, s_t \,.\, n \,.\, n_t \\ &= \frac{k \,.\, t \,.\, b \,.\, s}{12 \,.\, 33{,}000} \end{aligned}$$

(*k* in lb./in.²; *b*, *t* and *s* in in.)

As an example the net power requirements for the following milling operation in mild steel may be determined:

Cutter diameter d = 3 in.
Number of teeth n_t = 8
Cutting velocity v = 80 ft./min.
Feed rate s = 3 in./min.
Width of cut b = 4 in.
Depth of cut t = 0·2 in.

---

* G. Schlesinger, *Rechnungsgrundlagen zur Ermittlung des Leistungsbedarfes bei Walzenfräsern* (Determination of the power requirements of slab milling cutters by calculation), Werkstattstechnik 1931, p. 409.

$$n = \frac{12v}{\pi d} = \frac{12 \, . \, 80}{\pi \, . \, 3} = 102 \text{ rev./min.}$$

$$x_{\frac{\varphi_c}{2}} = \frac{s}{n \, . \, n_t}\sqrt{\frac{t}{d}} = \frac{3}{102 \, . \, 8} \, . \, \sqrt{\frac{0{\cdot}2}{3}} = 0{\cdot}00094 \text{ in.}$$

From Fig. 4.7: $k = 223 \text{ tons/in.}^2 = 500{,}000 \text{ lb./in.}^2$

$$\text{h.p.} = \frac{k \, . \, t \, . \, b \, . \, s}{12 \, . \, 33{,}000} = \frac{500{,}000 \times 0{\cdot}2 \times 4 \times 3}{12 \times 33{,}000}$$

$$\simeq 3 \text{ h.p.}$$

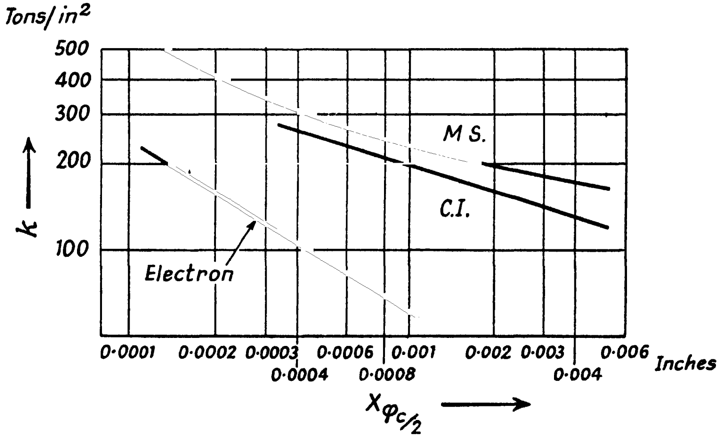


Fig. 4.7. Specific cutting resistances of M.S., C.I., and Electron

It is important to note that the power is not proportional to feed rate and depth of cut (as might appear from the above equation) because the value of *k* drops with increasing chip thickness (see Fig. 4.7).

By halving the depth of cut and doubling the feed rate, i.e. without changing the rate of metal removal,

$$x_{\frac{\varphi_c}{2}} \text{ becomes } \frac{0{\cdot}00094 \times 2}{\sqrt{2}} = 0{\cdot}00133 \text{ in.}$$

and *k* becomes 204 tons/in.^{2} = 456,000 lb./in.^{2} The net power required at the milling cutter is then

$$\frac{456{,}000 \times 0{\cdot}1 \times 4 \times 6}{12 \times 33{,}000} = 2{\cdot}75 \text{ h.p.}$$

On the other hand, by doubling the depth of cut and halving the feed rate

$$x_{\frac{\varphi_c}{2}} \text{ becomes } \frac{0{\cdot}00094 \times \sqrt{2}}{2} = 0{\cdot}00067 \text{ in.},$$

$$k \text{ becomes } 246 \text{ tons/in.}^2 = 550{,}000 \text{ lb./in.}^2,$$

and the net power required is

$$\frac{550{,}000 \times 0{\cdot}4 \times 4 \times 1{\cdot}5}{12 \times 33{,}000} = 3{\cdot}3 \text{ h.p.}$$

In other words, an increase of the depth of cut has a greater effect upon the net power required for cutting than an increase of the feed rate. In order to obtain a given rate of metal removal, it is more economical, therefore, to use a high feed rate and a small depth of cut. Furthermore, as the power consumption for a given rate of metal removal is lower the greater the chip thickness, it is advantageous, other cutting conditions being equal, to use cutters with a small number of teeth, because the feed per tooth, and with it the chip thickness, will be larger.

With increasing depth of cut the resistance grows, but the alternating component of the load pulsation may be reduced because a greater number of teeth is likely to be simultaneously in action. Too deep a cut has to be avoided, however, because of the danger of a cutting force component developing in a direction in which it may tend to lift the workpiece off the table.

For roughing cuts it is advisable to use low cutting velocities. The spindle speed (rev./min.) chosen for a cutter with a large number of teeth has to be lower than for one with a small number of teeth. This is important, not only from the point of view of power requirements, but also from the point of view of vibration, as the frequency of tooth impacts is equal to the product of the number of teeth and the spindle speed.

For finishing operations, and when using small-diameter milling cutters of low stability, higher cutting speeds are advisable in order to obtain good-quality surfaces at relatively high feed rates.

The frequency of markings on a surface machined by a milling cutter is not an indication of each tooth of the cutter but of each revolution. These markings are caused either by general eccentricity of the cutter or by a single tooth cutting at a larger radius than the others (Fig. 4.8).*

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* From A. J. Chisholm, J. M. Lickley and J. P. Brown, *The Action of Cutting Tools*, Machinery's Yellow Book Series No. 31.

As it is possible to obtain good surfaces by correctly selecting spindle speeds and table feeds, there is no point in using roughing cutters with small numbers of teeth and finishing cutters with large numbers of teeth. It is, however, important to realize that eccentricity of the cutter may not be due to the cutter teeth being badly ground. A distorted or bent milling arbor will also throw the cutter out of concentricity with its axis of rotation. Such bending of the arbor can be caused by the faces of the spacers on the arbor (see Fig. 4.25) not being parallel. Parallelism of these faces is therefore most important.

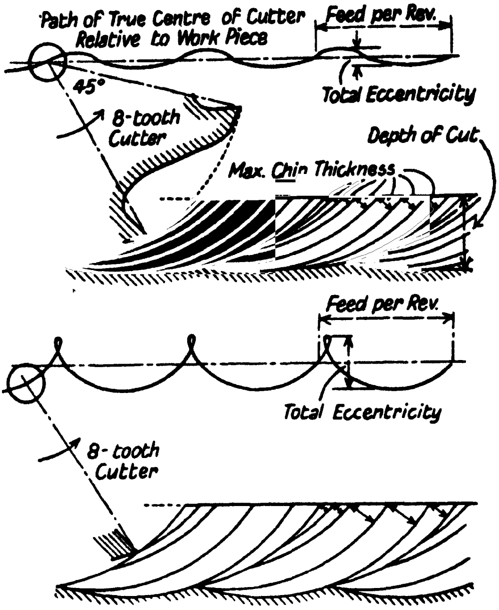

Fig. 4.8. Type of surface irregularity produced by eccentric slab milling cutters

Another point worth considering is the transmission of the torque from the milling arbor to the cutter. The arbor diameter is often relatively small compared with the outer cutter diameter, and torque transmission by friction between the faces of the spacers and the cutter is possible only if the axial clamping is very tight and the cutting forces are small. The former means an even greater danger of bending the arbor (see above), the latter, inefficient use of the cutter. If the cutting torque is too high to be transmitted by friction, the cutter will slip on the arbor, and breakage of teeth and/or damage to the surface of the workpiece may result. It is unfortunate that some machine operators try to save time and effort by not using keys and relying on friction for driving their milling cutters; this practice should be eliminated as far as possible.

The milling arbor is usually a weak link in the cutter drive, particularly because of the weakening effect of the key-way. External torque transmission devices on cutters and arbors (Figs. 4.9 and 4.22) eliminate this weakness.

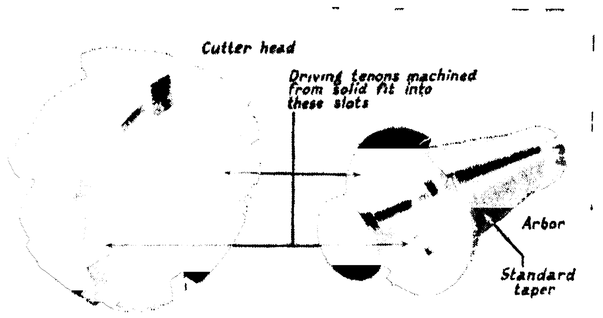

Fig. 4.9. Face Milling Cutter Head (Wickman Ltd.) with inserted blades and negative rake tungsten carbide tips and milling arbor with external drive arrangement

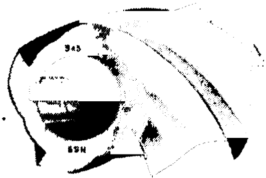

Fig. 4.10

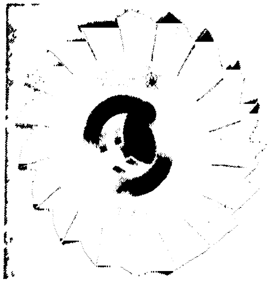

Fig. 4.11

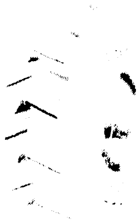

Fig. 4.12

Fig. 4.10. High power helical milling cutter (*English Steel Tool Corporation Ltd., Manchester*)

Fig. 4.11. High power side and face cutter (*English Steel Tool Corporation Ltd., Manchester*)

Fig. 4.12. Staggered teeth interlocked side and face cutter (*English Steel Tool Corporation Ltd., Manchester*)

In face milling the cycloids described by the cutter teeth lie parallel to the machined face (see Fig. 4.26). Because of the elastic recovery of the workpiece material and of the spindle location after

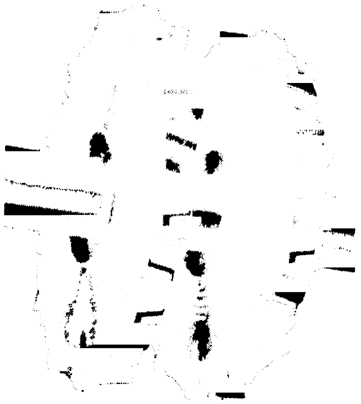

Fig. 4.13

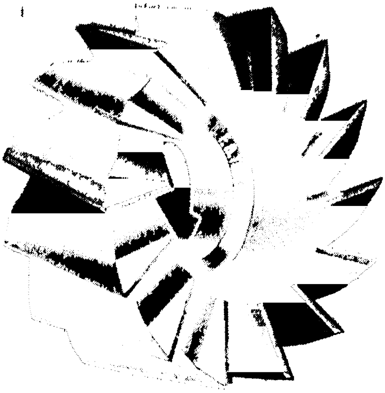

Fig. 4.14

Fig. 4.13. Serrated blade side and face cutters (*English Steel Tool Corporation Ltd., Manchester*)

Fig. 4.14. Shell end mill (*Firth Brown Tools Ltd, Sheffield*)

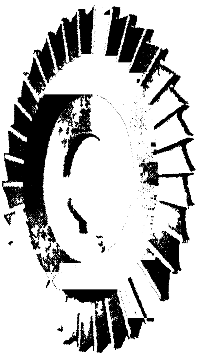

Fig. 4.15*a*

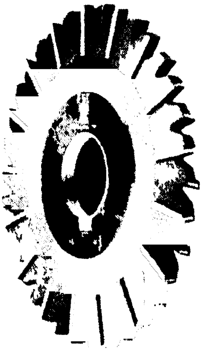

Fig. 4.15*b*

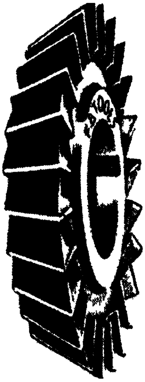

Fig. 4.16

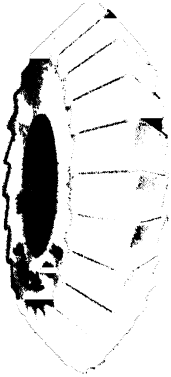

Fig. 4.17

Fig. 4.15. High speed steel side chip clearance saws (*a*) with ordinary teeth (*b*) with staggered teeth (*English Steel Tool Corporation Ltd, Manchester*)

Fig. 4.16. Single angle cutter (*Firth Brown Tools Ltd., Sheffield*)

Fig. 4.17. Double equal angle cutter (*Firth Brown Tools Ltd., Sheffield*)

each cut, a "back cutting" effect cannot be avoided, even with accurately-ground cutter teeth, unless the cutter spindle is tilted forward to produce a slightly hollow surface.

Some types of milling cutter generally in use are shown in Figs. 4.10 to 4.24.*

If sufficient power is available, several cutters of different diameters and shapes can be combined on an arbor as a "gang". Fig. 4.25 shows such a gang of large high-speed steel cutters for machining

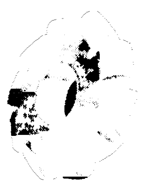

Fig. 4.18

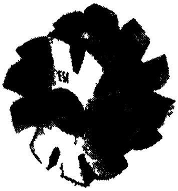

Fig. 4.19

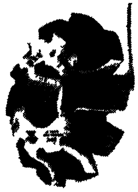

Fig. 4.20(*a*)

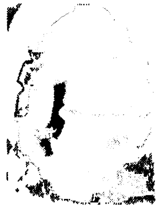

Fig. 4.20(*b*)

Fig. 4.18. Form relieved convex cutter (*English Steel Tool Corporation Ltd, Manchester*)

Fig. 4.19. Form relieved concave cutter (*English Steel Tool Corporation Ltd, Manchester*)

Fig. 4.20. Form relieved corner rounding cutters (*a*) single (*b*) double (*English Steel Tool Corporation Ltd, Manchester*)

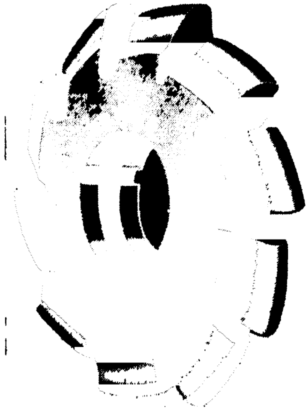

Fig. 4.21. Rotary form—relieved gear cutter (*Firth Brown Tools Ltd., Sheffield*)

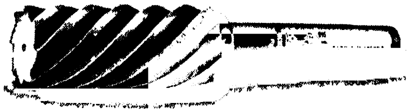

Fig. 4.22. Clutch drive side milling cutter (*English Steel Tool Corporation Ltd, Manchester*)

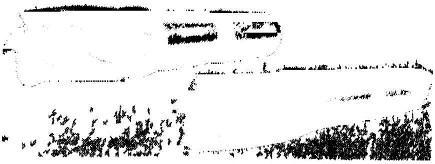

Fig. 4.23. Taper shank end mills (*Firth Brown Tools Ltd., Sheffield*)

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* For definitions see B.S. 122: 1953, Part 1: *Milling Cutters.*

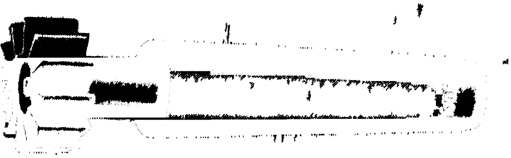

Fig. 4.24. Tee slot cutter
(*Firth Brown Tools Ltd*, *Sheffield*)

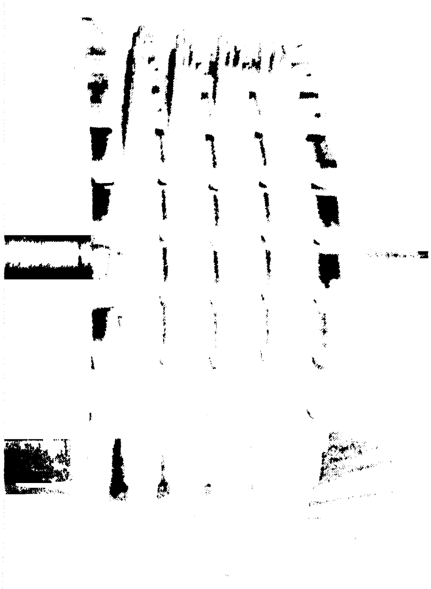

Fig. 4.25. Large diameter milling cutter gang
(*English Steel Tool Corporation Ltd*, *Manchester*)

high-tensile steel aircraft components. At the two ends of the gang are 15·2 in. diameter single angle cutters and between them are three 14·952 in. diameter double equal-angle cutters. It is advisable to use in such gangs cutters with opposite helix angles to reduce or eliminate the axial component of the cutting force.

For the same reason the staggered teeth of inserted blade cutters are often arranged in such a manner as to create opposing helix angles of the cutting edges (see Fig. 4.13).

For a given depth of cut the travel required to run the cutter into and out of the component depends upon the diameter of the cutter (Fig. 4.26). The smaller the cutter diameter, therefore, the shorter the total travel, and with it, the time required for a particular operation.

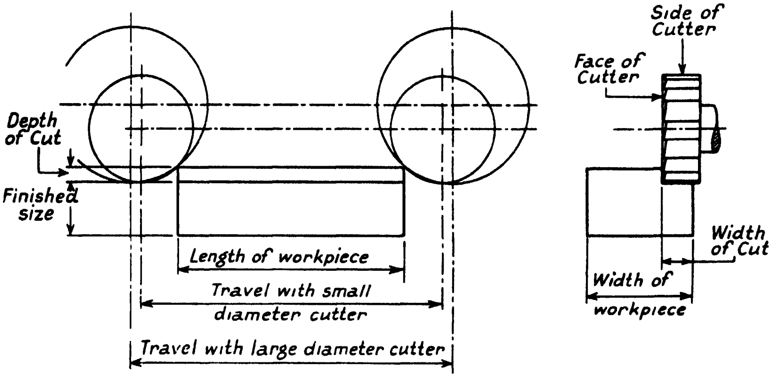

Fig. 4.26

On the other hand, the deflection of the arbor should not exceed 0·0005 in. and the cutter diameter must be large enough to allow an arbor of sufficient strength and rigidity to be used.

In face milling with cutter heads, a cutter diameter of 1·5 times to twice the width of cutting is recommended. This ensures that the cutter can enter the material at a favourable angle and leave it at an exit angle of about 45°.

In the before-mentioned considerations it was assumed that the cutter moved in a direction opposite to that of the feed movement of the workpiece. Although this method of cutting is more general, advantages can often be gained by employing the method of "down-cut milling", where the cutter teeth and the workpiece move in the same direction (Fig. 4.27), the vertical component of the cutting force then acting downwards and pressing the workpiece against the table, thus averting the tendency to loosen the grip of the clamps. This may be of importance when milling thin sections which are difficult to clamp and may be lifted from the supporting table if there is an upward component of the cutting force. Furthermore, the chip

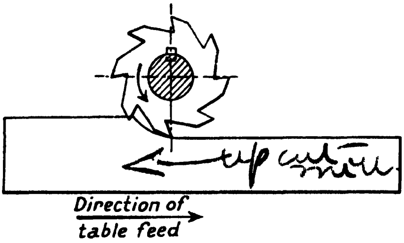

Fig. 4.27. Down-cut milling

thickness at the start of each cut is fairly substantial as compared with the infinitely small thickness of the cut made when the up-cut milling action starts, which may result in the cutter teeth rubbing rather than cutting. In down-cut milling, the angle of each tooth entering the material is much larger than in up-cut milling, and this is particularly favourable when a cutter with tungsten carbide teeth is used. The length of each tool path is shorter than during up-cut milling, and a better surface finish is sometimes obtained. Against these advantages it has to be remembered that the cutter always tends to draw the workpiece forward in the direction of the table feed. If, therefore, any backlash exists in the feed drive mechanism, or in the guiding devices of the table and its supporting members, or if the parts of the machine lack the necessary rigidity, the workpiece will be fed into the path of the cutter teeth at a rate which becomes

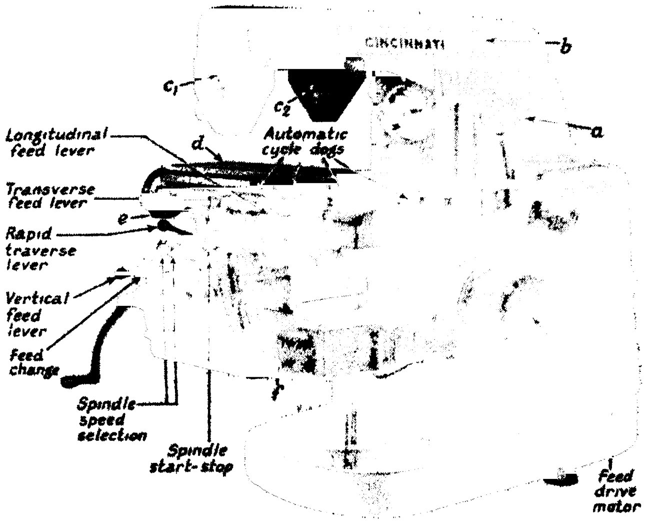

Fig. 4.28. No. 5 Dial type plain milling machine

Spindle drive 20 h p for spindle speeds 14–37 rev /min } 24 spindle speeds
40 h p ,, ,, ,, 46–1,400 rev /min
Feed drive 5 h p for feeds (0·375 90 in /min longitudinal and vertical
(32 feeds) (0 188—45 in /min vertical
Rapid traverse 150 in /min longitudinal and transverse
75 in /min vertical

(*Cincinnati Milling Machines Ltd , Birmingham*) intermittently higher than the one set for the job. The chip thicknesses will thus become greater than intended, and this may result in overloading the teeth, and in the cutter "climbing"* on to the workpiece instead of cutting into it. As a result the cutter and/or the workpiece may be damaged, the milling arbor bent, etc. Down-cut milling should therefore be attempted only on rigid milling machines with minimum play in slides and slideways and with devices which eliminate all backlash in the feed drive mechanism.

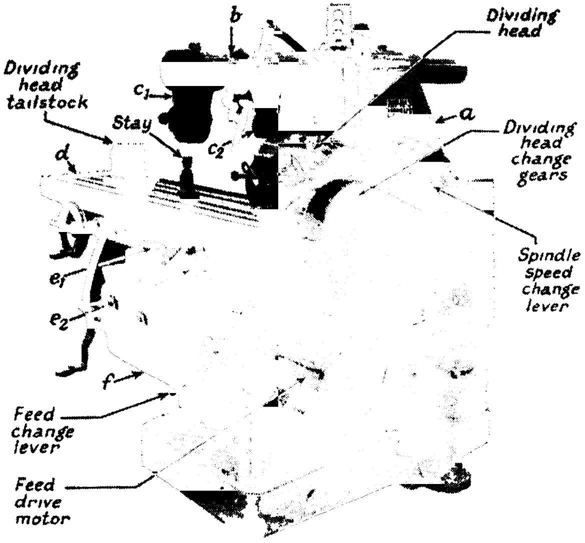

Fig. 4.29. No. 3 CE universal milling machine

(Manufactured by C.V.A. Jigs, Moulds and Tools Ltd., Hove, under licence from The Kearney and Trecker Corporation, Milwaukee, U.S.A.)

Milling Machines. The milling machines mainly used in engineering workshops are: (*a*) Knee-type machines; (*b*) Fixed-bed production machines; (*c*) Plano-millers.

Knee-type Machines. The spindle axis of knee-type milling machines is either horizontal (Figs. 4.28–29) or vertical (Fig. 4.30). The spindle bearings are usually stationary and rigidly fixed in the machine

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* For this reason the down-cut milling method is sometimes called "climb milling".

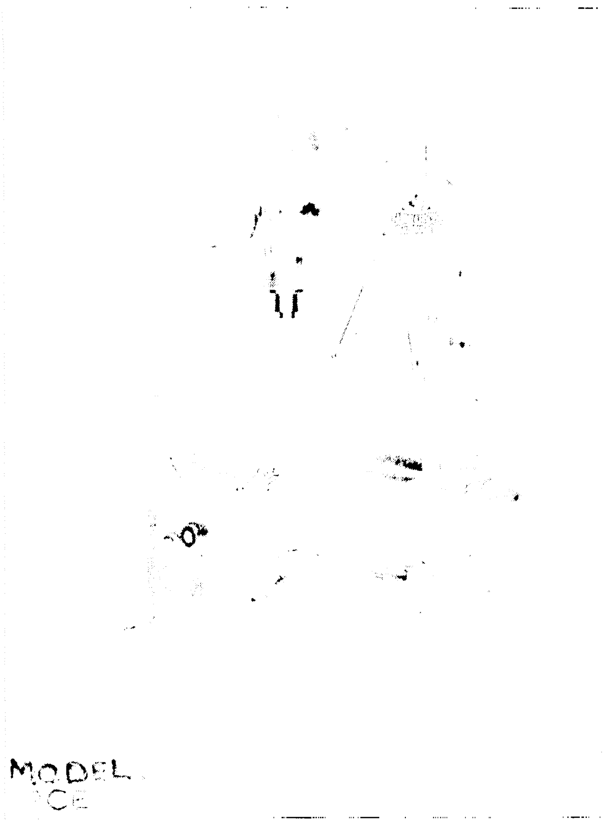

Fig. 4.30. No. 2 CE vertical milling machine

(Manufactured by C.V.A. Jigs, Moulds and Tools Ltd., Hove, under licence from The Kearney and Trecker Corporation, Milwaukee, U.S.A.)

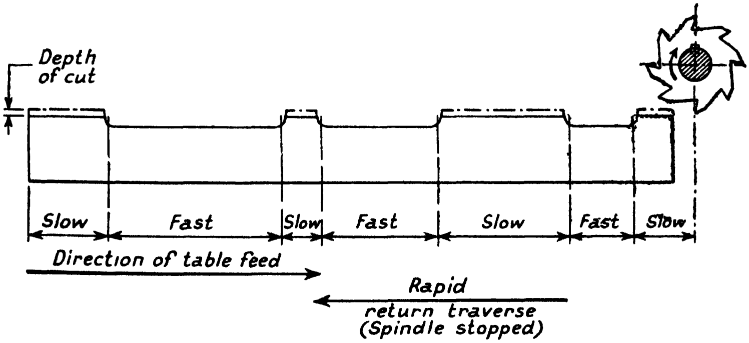

Fig. 4.31

upright (*a*, Figs. 4.28 and 4.29), although on some vertical milling machines (see Fig. 4.30) provision is made for an additional tilting and axial movement of the spindle. On horizontal machines (Fig. 4.28) the arbor, which carries the milling cutter or cutters (see Fig. 4.13), is supported by bearing brackets *c* on a rigid overarm *b*. The inner bracket c_2 should be set up close to the cutter to reduce the free length of the arbor and with it the bending-moment exerted by the cutting force. The workpiece is clamped on the table *d* which is movable longitudinally on saddle *e*; this can slide transversely on knee *f* which, in turn, can slide vertically along upright *a*. The table of universal milling machines (Fig. 4.29) can also be swivelled up to ± 45°* around the vertical axis; this movement is obtained by splitting the saddle into two parts, the top part e_1 being located in a spigot of the bottom part e_2. The universal milling machine is also equipped with a dividing head (see also page 136). This, together with the swivelling of the table, makes it, as its name implies, fully universal and capable of producing, for example, straight and helical teeth of clutches, gears, milling cutters, etc.

In addition to the usual feed driving gear, most modern milling machines have quick traverse drives for table, saddle and knee movements. The quick traverse drive serves for carrying out rapid setting movements, and for the rapid traversing of gaps in between machining operations (Fig. 4.31). On some machines, equipment is provided for the execution of automatic cycles, in which slow feed and rapid and return traverse can be initiated and stopped by appropriately-set trip dogs (see Fig. 4.28).

No feed movement must take place unless the spindle, and with it the milling cutter, is rotating, because cutter teeth would be seriously damaged if workpiece material were driven by the feed mechanism against a stationary milling cutter. On the other hand it is not advisable for a surface which has just been machined to be traversed rapidly past a rotating cutter which, due to a possible back-cutting effect (see page 126), may mark the surface. For this reason in many machines the spindle is automatically stopped as soon as rapid traverse is started. In machines with separate motors for the various drives (see Figs. 4.28–30) this can be achieved by electrical interlocks. Fig. 4.32 shows an electric circuit diagram for the fabricated milling machine shown in Fig. 15.22 of Part I of this work, where the spindle drive, feed drive and rapid traverse motors are electrically interconnected and interlocked.

* On some machines ± 90°.

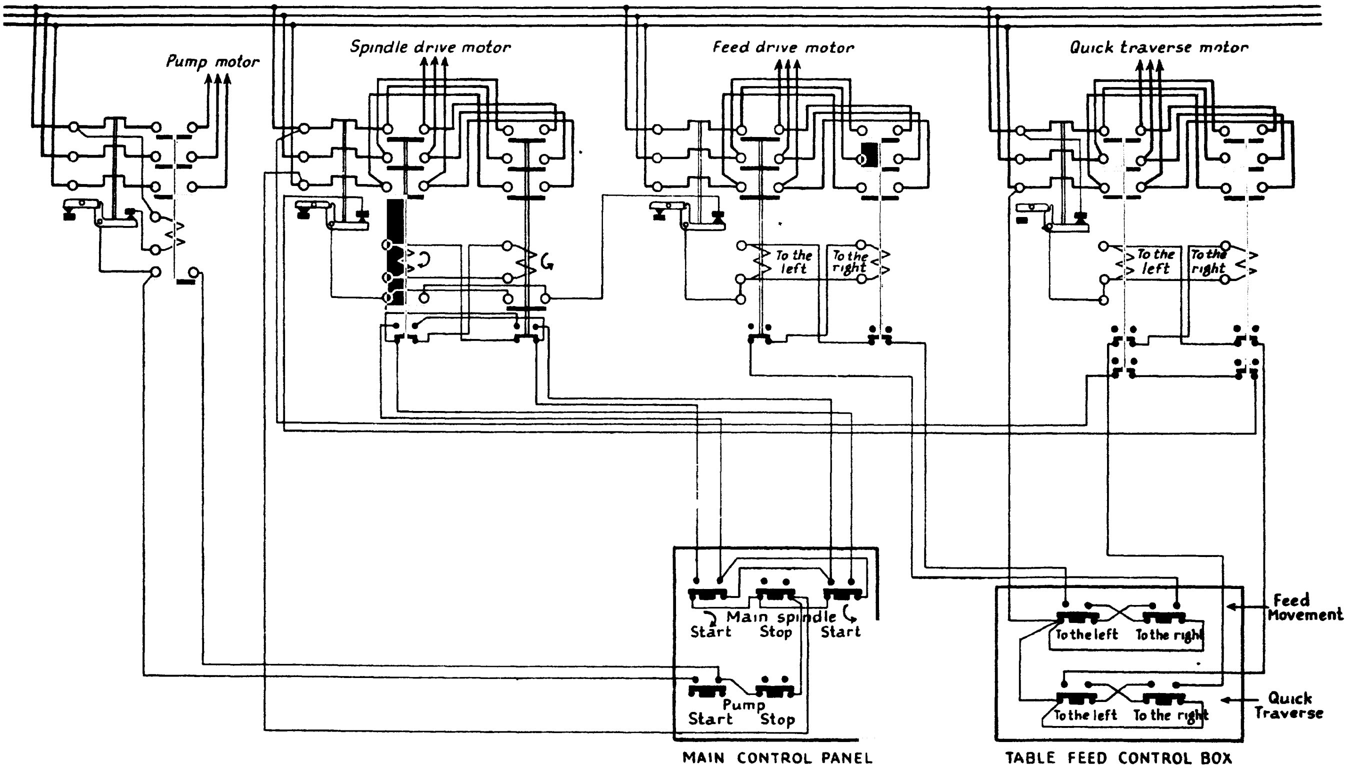

Fig. 4.32. Wiring diagram for milling machine described in Chapter XV of Part I

(*Cooke and Ferguson Ltd., Manchester*)

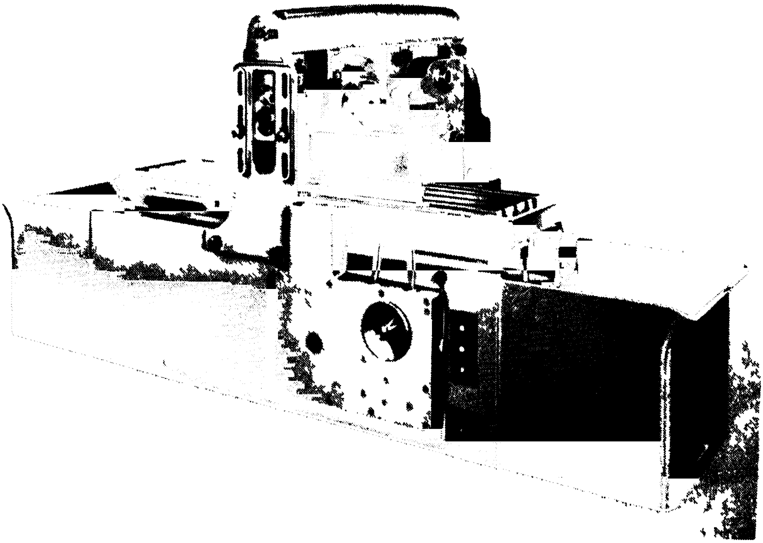

Fig 4 33 Plain Hypowermatic milling machine
(*Cincinnati Milling Machines Ltd Birmingham*)

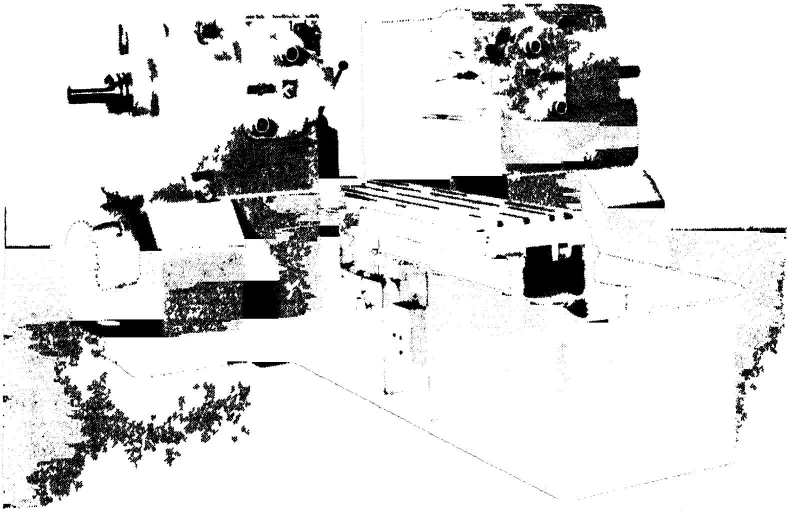

Fig 4.34 Duplex Hypowermatic milling machine
(*Cincinnati Milling Machines Ltd., Birmingham*)

The setting-up of knee-type milling machines is easy and can be carried out in a fairly short time. However, the superposition of three (longitudinal, transverse and vertical) or, in universal machines, four (longitudinal, rotating, transverse and vertical) movements which have to be aligned to a high degree of accuracy, makes the machines rather costly and is bound to affect their rigidity. They are, therefore, generally used as multi-purpose machines for "one-off" jobs and in tool rooms.

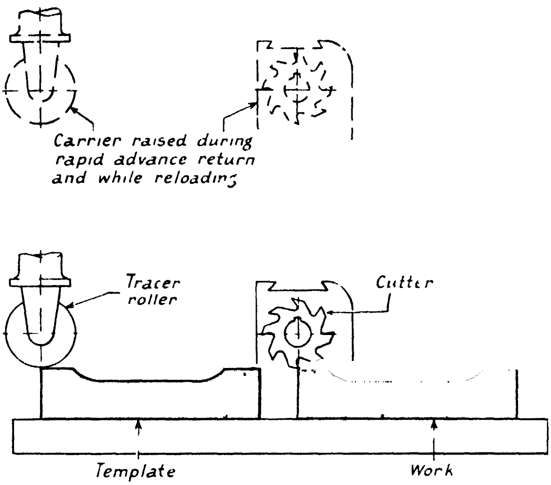
Carrier raised during rapid advance return and while reloading
Tracer roller
Cutter
Template
Work

Fig. 4.35. Principle of copy milling on a Cincinnati Hypowermatic machine

Fixed-bed Production Machines. For production jobs, where large batches of workpieces are machined, and where the times required for setting the machines are therefore not critical, the more rigid fixed-bed production machines are advantageous. The table of the single spindle machine (Fig. 4.33) and the two-spindle machine (Fig. 4.34) traverses longitudinally only. Transverse setting is effected by axial movement of the spindle which is carried in a sliding quill, and for vertical setting movements the spindle headstock can slide up and down the upright. The machines shown have a hydraulic table-feed drive. This consists of a hydraulic motor with infinitely variable speed, driving a worm and worm-wheel arrangement which in turn drives a table-rack by means of two pinions. A backlash-eliminating device making down-cut milling possible is incorporated in the drive.

Although the vertical setting movement is normally hand-operated, these machines can also be supplied with a hydraulic vertical drive which, in conjunction with a tracer device on the headstock and a template on the machine table, serves for copy milling profiles (Fig. 4.35).

Plano-milling Machines. For very heavy work, plano-milling machines—planing machines in which the planing tool-holders are replaced by milling heads—have been developed. The machine (Fig. 4.36) with four milling heads has been designed for operation on steel rolling-mill frames. The milling heads are equipped with 40 h.p. motors, and the table and the milling heads have infinitely variable feeds from 1 to 50 in./min., in addition to rapid-traverse and hand motion for setting purposes. The machine has the following capacity: 8 ft. 6 in. wide × 8 ft. 6 in. high × 26 ft. long.

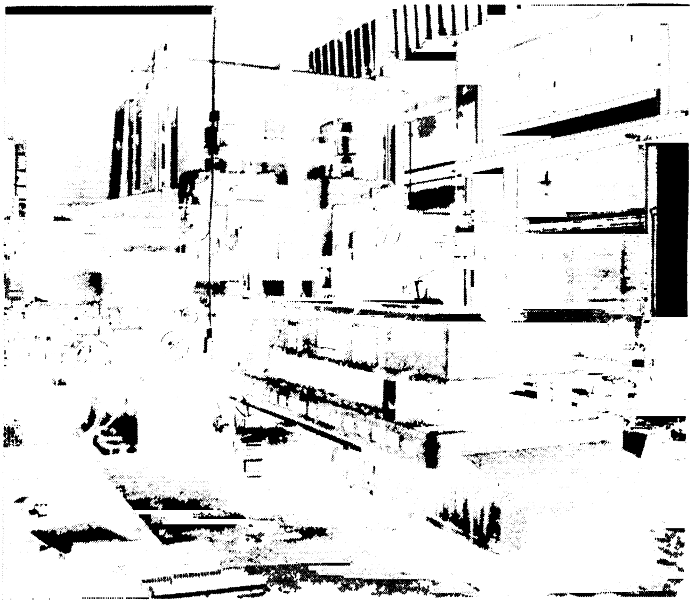

Fig. 4.36. Plano-milling machine

(Kendall and Gent Ltd., Manchester)

The Dividing Head. It is often necessary for equally-spaced grooves to be milled in the circumference of a circular workpiece. This means that after milling each groove the workpiece must be rotated around its axis by an accurate amount which corresponds to the number of grooves required.

When helical grooves have to be produced the workpiece must be rotated during the milling operation at a given ratio with the feed rate.

For this purpose the workpiece is put under the control of the work spindle of a dividing head, where it is either clamped to the work spindle itself or fixed between centres, one of which is held in the internal taper of the work spindle and the other in a tailstock (Fig. 4.37).

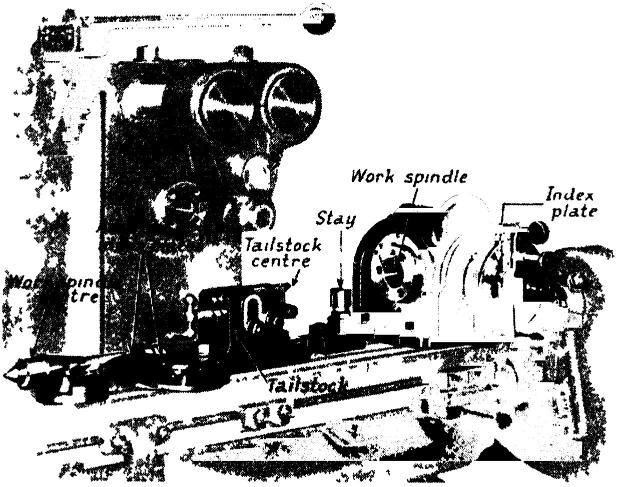

Fig. 4.37. Universal dividing head

(Manufactured by C.V.A Jigs, Moulds, and Tools Ltd., Hove, under licence from The Kearney and Trecker Corporation, Milwaukee, U.S.A.)

The actual operation of "dividing", i.e. the rotation of the work spindle by the intended amount, can often be carried out directly by means of an indexing plunger (Fig. 4.38) *a* and an index plate *b* on the work spindle itself *c*. The index plate usually has 24 holes equally spaced on a pitch circle,* the radius of which is equal to the centre distance between the indexing plunger and the work spindle. With 24 holes it is possible to carry out 2, 3, 4, 6, 8, 12 and 24 divisions. If other divisions are required they can be obtained by using a worm drive (ratio usually 1 : 40) between a dividing crank handle *d* and the work spindle *c*. The worm gear is usually designed with an adjusting device which makes it possible to reduce backlash to a

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* Sometimes up to three "hole circles" are provided, e.g. with 24, 30 and 36 holes.

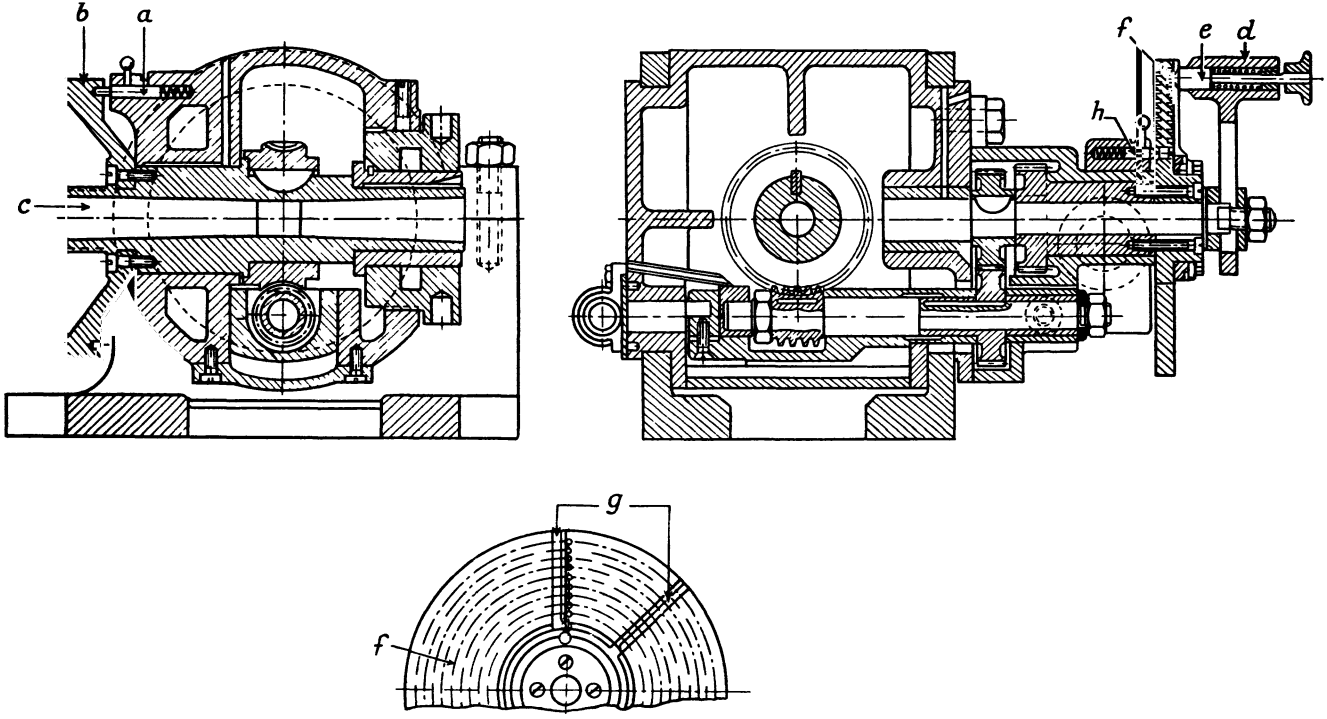

Fig. 4.38. Typical dividing head

minimum. The crank handle carries a spring-loaded indexing plunger e which can be inserted into any hole of a corresponding index plate f. The holes are arranged on the index plate in a number of "hole circles", each with a different number of holes equally spaced on its circumference, and the crank handle with the index plunger is radially adjustable on the worm shaft, so that the plunger can be set in line with the particular hole circle which will provide the required divisions.

As one complete turn of the crank handle represents $1/40$ of a turn of the work spindle, n turns of the crank handle represent $n/40$ turns of the work spindle, where n may be a whole number or a fraction. If, furthermore, the work spindle makes $n/40$ turns per division, the complete operation, e.g. in the manufacture of a gear wheel, will have been carried out after the work spindle has completed one turn, i.e. after $40/n$ divisions have been carried out. In other words the gear wheel which is being machined will have $T = 40/n$ teeth, and the amount n by which the crank handle of the dividing head has to be turned is $n = 40/T$, equal to 40 divided by the number of divisions, or the number of teeth of the workpiece.

In the very few instances where the worm-gear ratio in the dividing head is not 40, the actual value for the ratio will, of course, have to be inserted in place of 40. As mentioned before, n may be a whole number, a proper, or an improper fraction. If it is a fraction, the crank handle has to be moved over a number of holes equal to the numerator along the circle containing the number of holes equal to the denominator.

The index plates usually supplied with dividing heads have circles with the following numbers of holes:[*]

		15	16	17	18	19	20
21	23			27		29	
31	33			37		39	
41	43			47		49	

Example. A gear with 74 teeth has to be machined.

$$T = 74$$
$$n = 40/74 = 20/37.$$

The crank handle has to be set opposite the 37-holes circle of the index plate, and for each division the indexing plunger has to be moved 20 holes forward.

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[*] Today many universal dividing heads are equipped with a number of interchangeable index plates providing a much greater choice of hole circles. The principle of the matter is, however, unaffected by this.

To prevent the operator making counting errors, dividing heads are usually equipped with an adjustable set of sector arms (*g*, Fig. 4.38) which can be fixed to indicate the angle (determined by the number of holes to be covered) by which the crank handle has to be turned for each dividing operation.

The number of divisions obtainable with standard index plates is, of course, limited and there are divisions for which the available hole circles are not directly suitable. Some dividing heads are designed for using a combination of two different hole circles, so called "compound dividing". For this purpose a second indexing plunger (*h*, Fig. 4.38), usually located on the dividing-head body behind the indexing plate, can be set against one hole circle while the indexing plunger in the crank handle is used in addition in the usual manner. Compound dividing can be carried out if T is not a prime number and can be split into two parts, each representing the number of holes in an existing hole circle or a part or multiple of it. An example will explain the method:

$$T = 57. \quad n = \frac{40}{57} = \frac{40}{3 \times 19} = \frac{21 + 19}{3 \times 19} = \frac{7}{19} + \frac{1}{3} = \frac{7}{19} + \frac{6}{18}$$

Each division would then consist of two operations. If the fixed indexing plunger in the dividing head is opposite the 18-hole circle the index plate will be moved 6 holes along the circle, and after it has been fixed in its new position the crank handle, which has already been set opposite the 19-hole circle, will be moved 7 holes.

There are, however, many occasions when the number of divisions required is a prime number. In such cases "differential dividing" has to be used, a method in which the fixed worm-gear ratio of 1 : 40 is transformed into a variable one. This is achieved by unlocking the, normally fixed, index plate and coupling it, by means of change gears, with the work spindle.

In this manner the index plate can be made to rotate during each dividing operation either in the same or in the opposite direction of the dividing movement of the crank handle and by an amount determined by the change-gear ratio. If, for instance, the gear ratio between the work spindle and the index plate is 1 : 1, the index plate will make one complete turn for every 40 turns of the crank handle. If the index plate rotates in the same direction as the crank handle, 39 turns of the crank handle in relation to the index plate will result in one complete turn of the work spindle; in other words, the effective ratio between crank handle and work spindle will have been

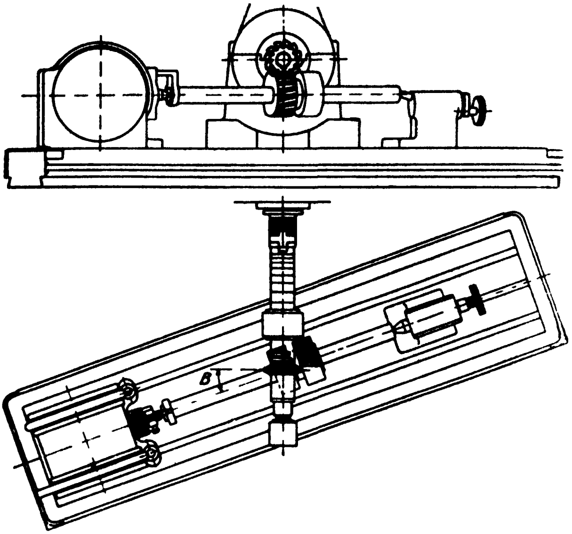


Fig. 4.39. Milling of helical teeth

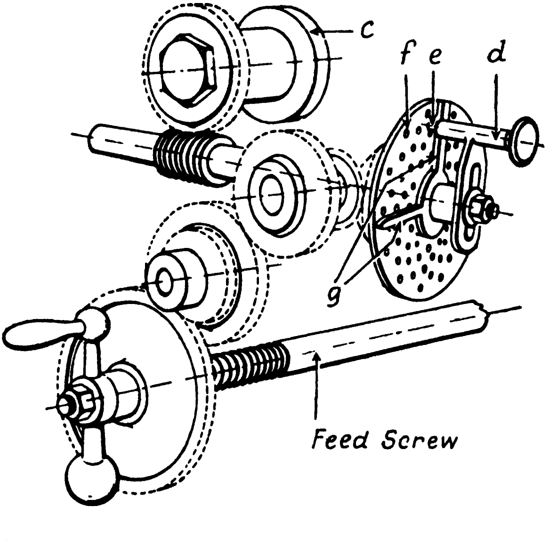


Fig. 4.40. Mechanism of dividing head with drive for milling of helical teeth

changed from 1 : 40 to 1 : 39. Similarly, by introducing an intermediate gear and making the index plate turn in the opposite direction, the effective ratio between crank handle and workpiece becomes 1 : 41. An example will best show the application of the principle'

A gear wheel with $T = 97$ teeth is to be machined on the universal milling machine. With each division, therefore, the work spindle of the dividing head should make 1/97 of a turn. The nearest division which can be obtained without differential dividing may be 1/100, and 100 may be called the auxiliary dividing factor X. The corresponding value of n is $n = 40/100 = 8/20$ (8 holes on the 20-holes circle). As, however, 97 divisions have to be executed for a complete turn of the work spindle the index plate must rotate forward by an amount of $3 \times 40/100$ during these 97 divisions. In other words the index plate must be driven by the work spindle in the direction of the crank handle movement at a ratio of $i = 3 \times 40/100 = 6/5$, and this ratio must be obtained through the fixed ratio (bevel or worm gear, etc.) provided in the dividing head and the change gears, which have to be chosen accordingly.

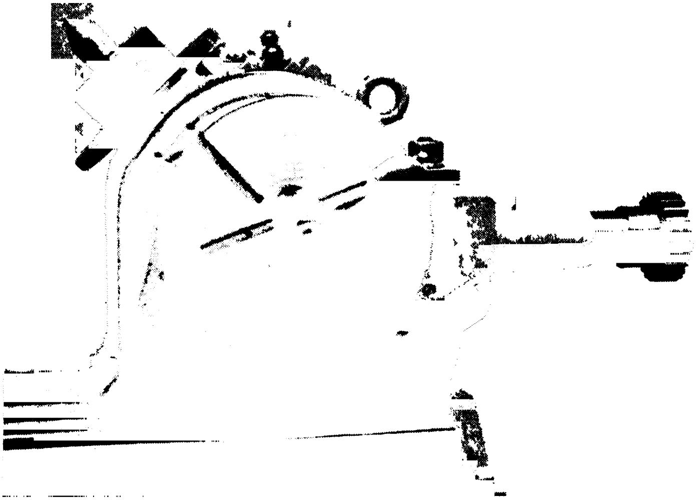


Fig. 4.41. Universal dividing head used in Royce laboratory of the Manchester College of Science and Technology

(J. Parkinson and Son (Shipley) Ltd, Shipley)

If the gear ratio in the dividing head is 1 : 1 the required change-gear ratio is $i = (40/X) \times (X - T)$.

The value 40 is again, of course, only applicable if the worm-gear ratio in the dividing head is—as it is in most cases—40. Otherwise the corresponding value has to be used in the equation. If X happens to be smaller than T, and if therefore i becomes negative, an intermediate gear has to be inserted to make the index plate rotate in a direction opposite to the rotation of the crank handle.

For milling helical grooves the table has to be set at an angle equal to the helix angle (Fig. 4.39) and the table-feed screw of the milling machine is connected, by means of change gears of the required ratio, to the drive of the index plate which must be free to rotate and therefore disconnected from the dividing-head body (Fig. 4.40). After each run of the milling cutter, and when the feed screw, and with it the index plate, is stopped, the ordinary dividing operation can be carried out by turning the crank handle against the index plate. It will be appreciated, however, that in this case neither compound nor differential dividing is possible.

The required accuracy in milling helical grooves can be obtained only if the vertical axis of the table swivel intersects with the horizontal axis of the milling cutter and that of the workpiece. For this reason the axis of the swivelling spigot in the saddle must be accurately aligned, not only with regard to the main spindle but also with the centre T-slot of the table, because tenons in the base of the dividing head fit into the centre T-slot of the table and thus locate the work-spindle axis in line with the T-slot centre line.

For milling cams, bevel gears, etc., the universal dividing head can be tilted up to 90° (Fig. 4.41). As the tilting axis coincides with the axis of the indexing plate, the position of the latter is not affected by the tilting operation, and the dividing head can still be driven by the table screw via change gears, thus making the milling of flat cams etc. possible.

For Bibliography see end of book.

CHAPTER V

DRILLS AND DRILLING MACHINES

By F. M. BIRCH, A.M.I.PROD.E.
Jones and Shipman Ltd., Leicester

DRILLING machines are normally employed for producing circular holes in varying types of material, though some of them can be adapted to perform other operations such as tapping, spot facing, reaming, etc. The essential feature is a revolving spindle which holds the drill or other tool, and which can be fed towards the component which is fixed to the table or to the base of the machine. Generally the requirements of a good machine are accuracy, long life, and convenience; the spindle speeds and the arrangements for varying the feed or cut must be satisfactory and suitable for the work for which the machine is intended.

Drills. For many years twist drills have been used for most drilling operations—both on standard and special drilling machines, and on lathes of various types. They are probably the tools most used in production work. Twist drills were originally made from carbon steel (hardened and tempered); but for heavy-duty drilling, and for large output, high-speed steel has largely superseded carbon steel, and, although both types are available, high-speed steel-drills are now standard where output is important.

The use of high-speed drills has affected the design of drilling machines because higher drill speeds and heavier feeds can be used. The main alterations have been the use of ball bearings instead of plain journals running in ordinary brasses, and the general strengthening of drill columns and framework. A better understanding of efficient drill speeds has led to a better range of spindle speeds, and to a more variable rate of feed.

Standard twist drills are made with two cutting edges(Fig. 5.1) and two opposed spiral flutes, which serve to provide clearance for the chips or spirals of metal removed by the cutting edges.

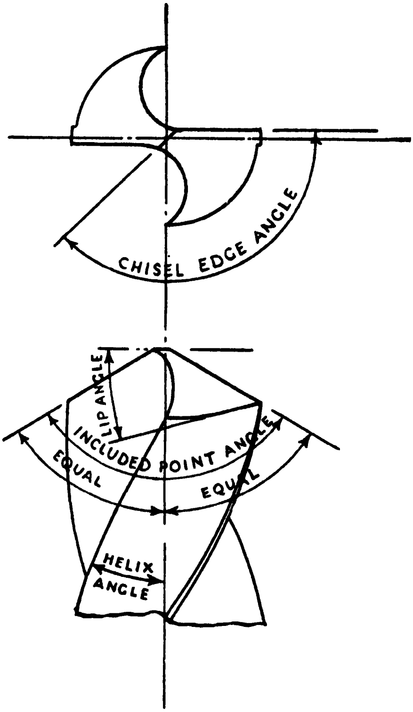


Fig. 5.1. Standard type of drill with helix angle of 20°–32°

Material	*Point angle*	*Lip relief angle*	*Chisel edge angle*
STEEL—low carbon, forged, annealed or cast	118°	12–15°	125–135°
NICKEL, MONEL, and other soft NICKEL ALLOYS	118°	12–15°	125–135°
STEEL:			
Hard, inc. nickel steel up 200 Brinell	118°	6–9°	120–130°
Hard, inc. nickel steel up to 200/300 Brinell	130–140°	5–7°	115–125°
Hard, inc. nickel steel up to 300/400 Brinell	140–150°	5–7°	115–125°
Nitriding, about 250 Brinell	130–140°	5–7°	115–125°
Nitriding, free machining	118°	10°	125–135°
Stainless	118–140°	5–7°	115–125°
High speed	135°	5–7°	115–125°
NICKEL ALLOYS (hard), e.g. Inconel, etc.	135–410°	5–7°	115–125°
CAST IRON (soft)	90–118°	12–15°	125–135°
CAST IRON (chilled)	118–135°	5–7°	115–125°
MARBLE	90°	12°	125–135°
SLATE	118°	12–15°	125–135°

Figs 5.1–5.5 *and accompanying data were supplied by Jones and Shipman Ltd.*

The Cutting Edge. The diagrams in Figs. 5.2 to 5.5 indicate the variations in cutting edges and spiral flutes needed for drilling various metals and alloys. The efficiency of a drill depends almost entirely on the accuracy of the cutting edge, and unless the cutting edges are ground correctly the advantages of a modern drilling machine are wasted.

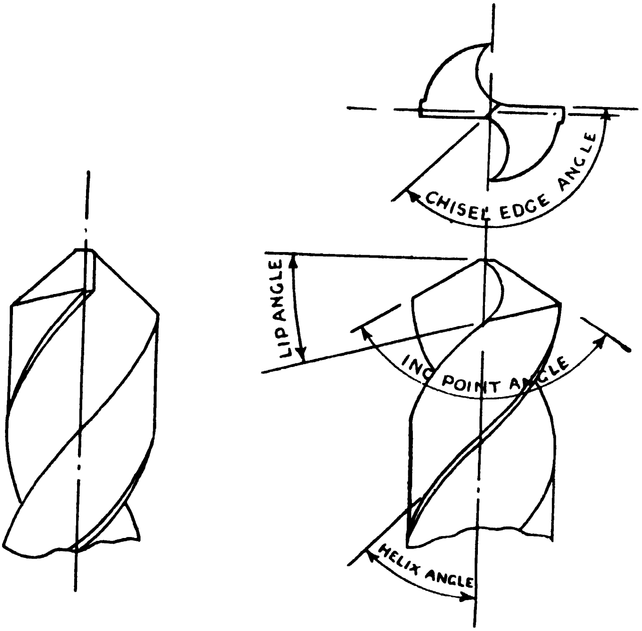


Fig. 5.2. Drills with quick spiral flutes

Material	*Point angle*	*Lip angle*	*Chisel edge angle*	*Helix angle*
Magnesium Alloys	118°	12–15°	135–150°	40–45°
Aluminium Alloys	118–130°	12°	125–135°	32–45°
Die Castings, Zinc, etc.	90–136°	12–20°	125–135°	32–45°
Copper and some Copper Alloys	100–130°	10–15°	125–135°	30–40°

The essential features of a good drill point include: (1) equal lip angles and equal length of lip, with the point exactly in the centre, failing which the resulting hole will be oversize by an amount approximating to twice the difference in lip length; (2) correct lip clearance. The cutting edges trace a spiral created by the circular motion of the drill and by the feed or forward motion of the drill; the portion of the drill point behind the cutting edge must clear this spiral, and, at the same time, each cutting edge must have as much support behind it as possible to prevent the edge breaking down under pressure, or through overheating.

The variation in lip angle (Fig. 5.1) shows that hard materials require a smaller lip clearance than those which are softer, and are drilled with finer or smaller feed per revolution.

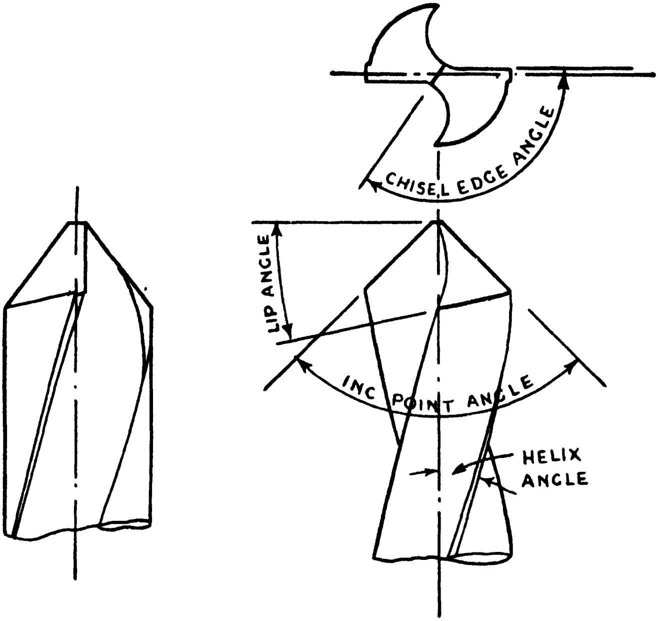
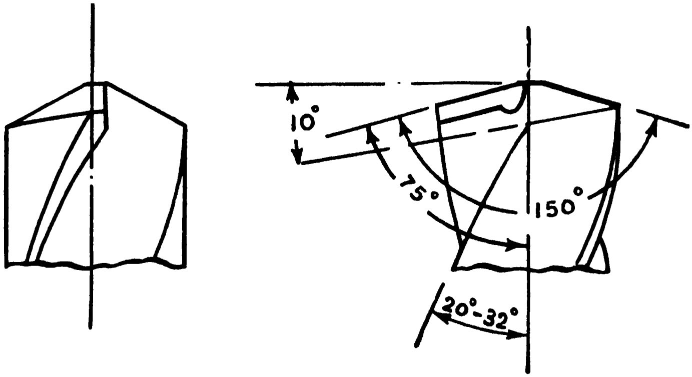


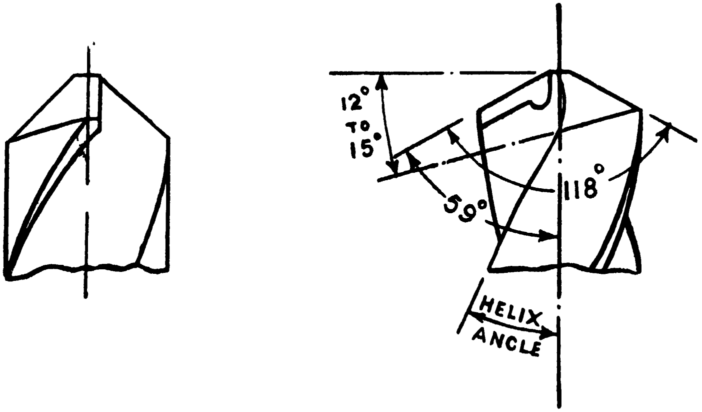
Fig. 5.3. Drill with slow spiral flutes

Material	*Point angle*	*Lip angle*	*Chisel edge angle*	*Helix angle*
Hard Bronze, including aluminium bronze and manganese bronze	118°	5–7°	115–125°	10–30°
Plastics, bakelite and hard rubber	90–118°	12–15°	125–135°	10–20°
Fibre	90°	12–15°	125–135°	17–20°

The importance of correct sharpening or grinding of drill points has lately been appreciated, and in modern factories drills are treated in a similar manner to milling cutters and like tools. Grinding is undertaken by a special department of the tool-room, or tool-store, on machines specially built for the purpose. The fallacy of each man being allowed to grind his own drills by hand to suit his own particular whims has been revealed by the outstanding performance of drills correctly ground on well-designed machines.



(*a*) Chisel edge 125–135°, for brass and bronze (Helix angle: soft, 10°–30°; free machining, 0°–20°,



(*b*) Chisel edge 115–125° for steel rails (7–13 per cent manganese)

Fig. 5.4. Drills with flattened lips

Drilling Feeds and Speeds are usually taken from handbooks and tables, but these must not be followed too closely as circumstances vary with the type and rigidity of machine in use. The feed rate depends primarily on the strength of the twist drill, the rigidity of the machine, and the power of the driving motor. There is considerable information available as a result of recent research, which is still continuing, but this is rather too technical to be of use to the average drilling machine operator. Manufacturers of drilling machines will usually supply data showing the economical performance of any particular unit, and this information should be made available to the operator.

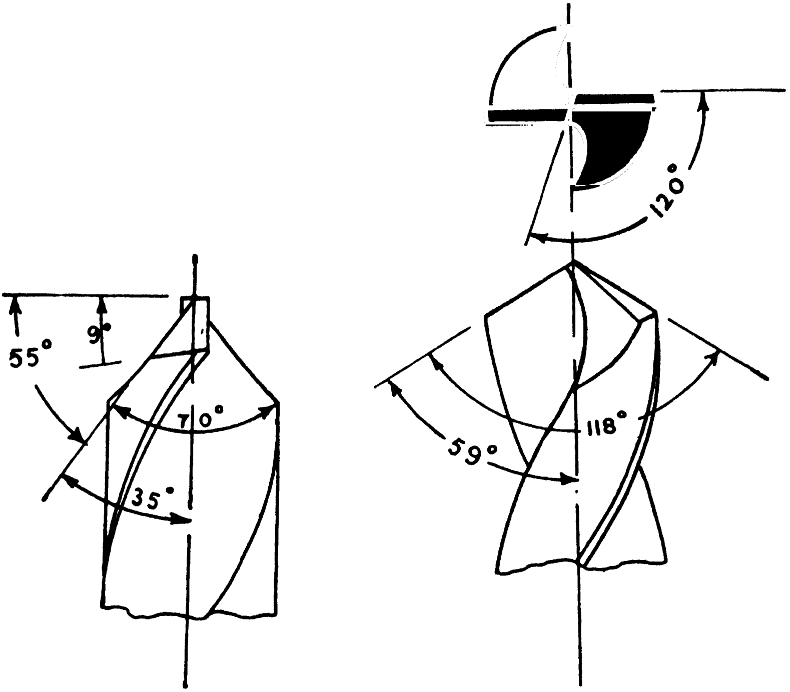


Fig. 5.5. Crankshaft and deep-hole drills

Types of Machines. As drilling machines are employed for drilling holes from 0·010 in. to 3 in. diameter or over in varying materials, the designs vary considerably. They can, however, be divided into classes as follows:

Super-sensitive machines for holes from 0·010 in. to $\frac{1}{16}$ in. diameter.

Sensitive machines for holes from $\frac{1}{16}$ in. to $\frac{3}{4}$ in.

General-purpose machines for holes $\frac{3}{4}$ in. upwards.

In addition to these there are radial drilling machines, semi-automatic machines of varying types, special-purpose machines, and self-contained units which can be mounted on a framework to form high-production semi-automatic machines.

Super-sensitive Drilling Machines are employed for drilling extremely small holes in components such as diesel fuel-pump injection nozzles. The characteristics required are extremely high speeds (around 20,000 r.p.m.), and particularly sensitive feed control. In using drills of such small diameter automatic feeds are seldom employed, as variation in the cutting quality of the material being drilled has a very marked effect on the drill. By utilizing a feed control which is operated by the thumb or finger, the cutting effect of the drill is transmitted to the operator by feel or touch, and the rate of feed can be varied at will to suit the conditions. Feeding with a dead weight controlled by a dash pot is sometimes employed, the dash pot being set to limit the rate of penetration by adjustment of the rate at which fluid can be passed through a small orifice by the advance of a piston.

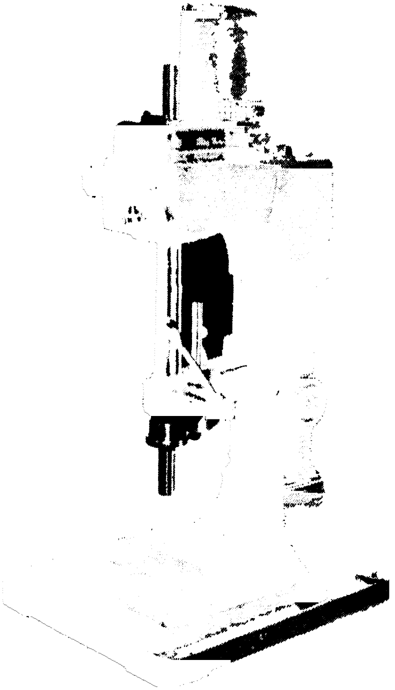


Fig. 5.6. High-speed sensitive drilling machine

(*Jones & Shipman Ltd.*)

High-speed Sensitive Drilling Machines (Fig. 5.6) are used for drilling holes from $\frac{1}{16}$ in. to $\frac{3}{4}$ in. diameter. The methods employed for obtaining speed changes vary from cone pulleys and belts, on the smaller machines, to gear-boxes and variable-speed motors, on the larger.

The cone-pulley and belt-drive machines usually have a constant-speed motor mounted at the rear of the head, with a cone pulley attached to the motor shaft, for driving the drill spindle by means of vee or flat belts. Varying speeds are obtained by moving the belt on to the different diameters of the cone pulleys. Being of simple construction this type of machine is cheap. As the present Home Office regulations insist on the driving-belts being totally enclosed, frequent speed changing is not convenient, and where such is necessary it is usual to employ a gear-driven machine. The gear box is of the sliding-gear type, and, to prevent damage to the gears upon changing, the gear-change lever is coupled to the switchgear in such a manner that the driving motor is automatically switched off when the lever is moved out of the locating slot to pass through the gate to the next gear position.

Pole-change Drills. For light-duty drills, a pole-change motor forms a very useful form of drive, by which from two to twelve different speeds can be obtained. In the case of a three-phase motor (this system is only used for multi-phase supplies), the speed depends on the number of poles the motor has, or, alternatively, the number of poles connected to the supply. So, by using a special control switch and a specially designed motor, it is possible to obtain a range of speeds by simply moving the control switch. Normally about four speeds are used because the arrangement is rather costly with more, and becomes electrically inefficient at certain ranges. The pole-change drill is most useful for occasional work for it is very simple to use and gives a useful range of speeds, such as 3000, 1500, 750 and 500 r.p.m. Different ranges, in the same steps, can be obtained by means of gearing.

One disadvantage is that the power of the motor is roughly proportional to the speed, and so extra power is available when drilling small holes at high speed. This may be undesirable with ferrous materials but for brass and aluminium it may be very useful.

General-purpose Machines. A typical medium or heavy-duty drill (Fig. 5.7) should be reasonably accurate over a long life and, at the same time, be capable of a high output, particularly with the larger sizes of drill which it is designed to take. Easy maintenance is, of course, essential in avoiding loss of accuracy with long use.

In general, these drills are fitted with direct motor drive, through two gear boxes: one giving the required drill speeds, and the other varying the rate of feed. Gear boxes have now replaced the cone pulleys and belts (with back-gearing in many cases to obtain slow speeds), and the modern designs give a very clean machine with all controls at the operator's hand.

A large handwheel gives instantaneous control of the spindle feed and the slightest movement backwards disengages the feed under the heaviest load. The spindle speed and rate of feed are varied by levers; starting and stopping are by push-button switches. In this particular case the rise and fall of the table is effected by another electric motor, seen (Fig. 5.7) on the right of the table assembly. The suds pump is placed at the back of the base. For high, accurate output it is essential for the operator to be able to control all motions with the least effort and without taking his eyes off the work too often.

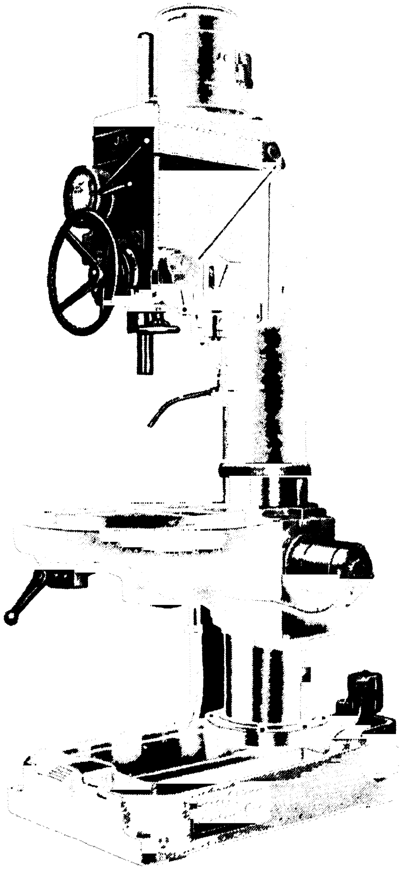


Fig. 5.7. Medium or heavy duty drill

(Jones & Shipman Ltd.)

Provided the bearings are suitably designed a drill of this type has a limited use for vertical boring.

Radial Drilling Machines. The main advantage of a radial machine is that the drill can be moved over the work to any desired position, so that a large number of holes can be drilled in the work without moving it. This type also has the advantage that large and heavy castings can be placed on the bed and drilled without locating them accurately. Light-type radial drills are used for such work as drilling girders used in construction work, whereas heavier types may be used for drilling the holes in the flanges of large diesel engine cylinders.

The drilling head (Fig. 5.8) is mounted on an arm, which is arranged to swivel round a fixed column and along which the head can be traversed. All variations in spindle speed and feed are by gear boxes, and, in many cases, each operation (drill drive, traverse, rise and fall of the arm, etc.) has its own separate motor. Radial

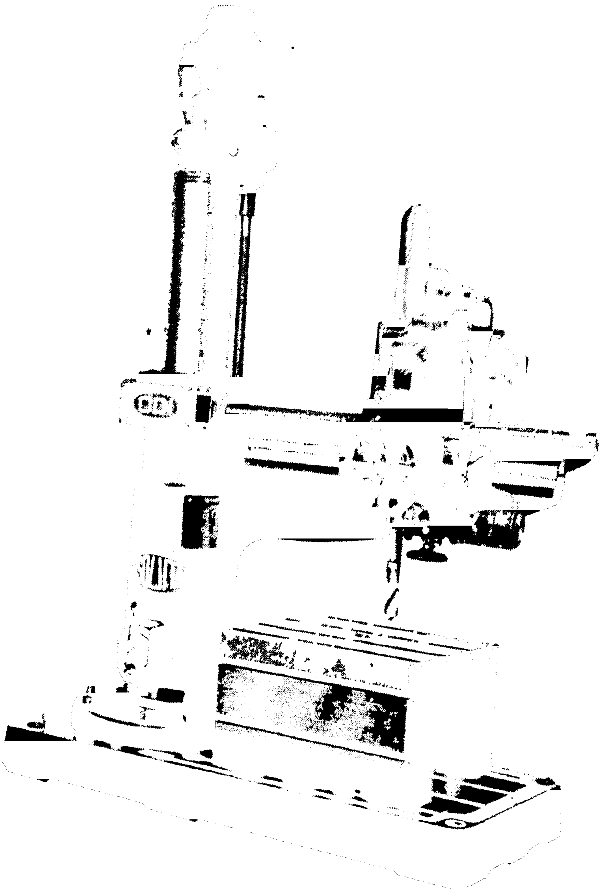


Fig. 5.8. Modern radial drilling machine

(*Wm. Asquith Ltd.*)

drills are invariably of the highest quality and are particularly valuable where there is sufficient work to repay the cost.

Multi-spindle Machines. Sensitive drills for light, accurate work are often fitted with a number of heads on one column (Fig. 5.9).

A multiple-spindle machine can perform a number of operations on a component without the necessity of changing tools or removing

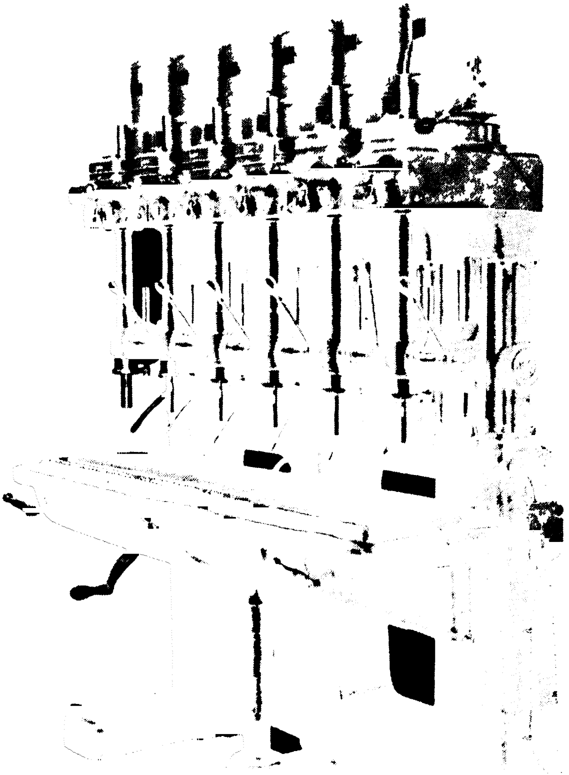


Fig. 5.9. Multiple-spindle drilling machine

(*Jones & Shipman Ltd.*)

the component from the jig. A six-spindle machine might be used with a $\frac{15}{64}$ in. diameter drill in the first spindle, a $\frac{3}{8}$ in. counterbore in the second, a $\frac{7}{16}$ in. tapping size drill in the third, a countersink in the fourth, a tap in the fifth, and a reamer in the sixth. The component can then be passed from spindle to spindle until it has traversed the length of the table and all the operations are completed. Each spindle would be set to run at the correct speed for the operation required, the fifth spindle, which is required for tapping, being fitted with a reversing mechanism.

Multi-spindle Attachments. The need for drilling a number of holes in large batches of components has led to the use of multiple-spindle attachments. An example is the drilling of four or eight holes in pipe flanges. These attachments consist of a framework or box carrying the required number of spindles, each being driven by the main drilling machine spindle. A five-spindle attachment is shown in Fig. 5.10. Once the component is correctly located, probably by a jig, all the holes are drilled accurately at the same time.

This type of attachment is much used in the aircraft and automobile industries. In some models it is possible to alter the various trains of gearing in order to allow the use of different sizes of drills.

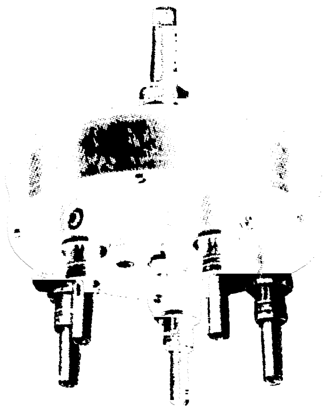


Fig. 5.10. Multiple-spindle attachment
(*Jones & Shipman Ltd.*)

Tapping Reverse. When drilling machines are used on production work for tapping threads the spindle must be reversed to withdraw the tap. A tapping attachment may be used which provides this reverse, though drills can be obtained with it incorporated in the machine. The spindle into which the tap has been mounted is fed down to the job by hand, and, as the tap commences to cut, it will feed automatically as the thread is cut. When the required depth is cut, the rotation is reversed and the tap screws itself out of the hole.

Several methods of reversing are employed, but for light, sensitive machines, which are capable of tapping small holes at high speed, an attachment is used which consists of a double friction clutch. By means of gearing in the attachment, the upper and lower clutches are run in opposite directions and the main spindle is arranged to engage the appropriate clutch for forward or reverse direction of rotation.

General-purpose machines are usually equipped with gears operated by dog clutches, or friction clutches operated by means of a lever or pedal. Alternatively, the direction of the driving motor may be reversed, though this is possible with three-phase motors only, owing to complications with single-phase or D.C. supplies. The latest electronic devices, which are being developed to give a greater degree of control over motor speeds, may be the ideal solution. Special motors are already available for withstanding the heavy loads caused by continuous starting and reversing.

Automatic Drilling Machines. The machines described so far have been of the more standard type for use in general engineering shops, and for performing certain kinds of production work. For quantity repetition work special machines are available, being either *automatic* or *semi-automatic.*

FIXED COMPONENT OR FIXED TABLE TYPE. To understand this type of machine, imagine that the component to be drilled is a motor-car cylinder block, or gear box casing, where there are groups of holes on various sides, some often being at compound angles. The procedure is to hold the component in a jig (usually pneumatically operated), and to present the component at various angles to multiple-spindle attachments, which can drill all the required holes at the same time. Each multiple-spindle attachment is driven by a *unit drilling machine* designed to work in a horizontal or vertical plane, or at any angle. Each unit has its own master switch. Special types of drilling heads with self-contained feed motions have been developed for this type of work; they are usually mounted round the centre block or jig.

The component is placed in the jig or fixture and held by means of clamps operated by compressed air or hydraulic devices. The master start button is pressed and all the spindles carrying the multi-drill heads feed forward, the drills revolving at their respective speeds. Each head is set to feed forward to a pre-set depth controlled by a limit switch, and each head then returns to the start position; its drills stop while a new component replaces the one just finished. A very high output can be achieved. The main cost is in tooling and setting up (this must be done to a high degree of accuracy), the process being economical only for very large quantities.

As the drill heads are in unit form, any change in the design of the component or of the holes can be arranged for by adjustment, and more or fewer heads can be used where required.

INDEXING TABLE TYPE. This type of machine is used to perform several operations—often multiple—on smaller types of components, the operations taking place in sequence.

The table is arranged so that it can be moved round, or indexed, into a definite number of positions, or stations, for each revolution of the table. The component is fixed into a jig at the loading station and moved round to the unload position. Multi-spindle drill heads may be arranged to operate at each stage, and each operation is generally dependent on the preceding one.

If, for example, we require four holes to be drilled, to be spot-faced, and finally to be tapped, the table would be indexed as shown in Fig. 5.11, and the layout for the job would read:

1st station	load
2nd station	drill 4 holes
3rd station	spot-face 4 holes
4th station	tap 4 holes.

All the spindles feed down together, and the appropriate operation is performed at each station simultaneously, the unloading and loading being carried out at station 1. Although the various operations will not take the same length of time, the sequence is economical, because, in any case, the rate of production is governed by the slowest process. Only where there was a very great discrepancy would some other production method be used.

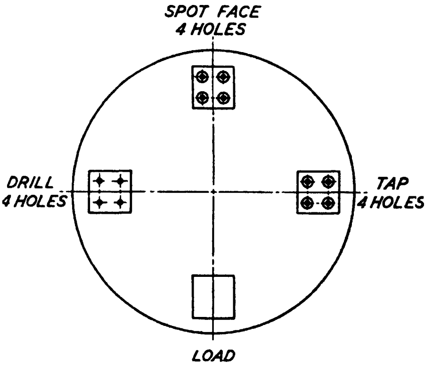


Fig. 5.11. Layout for indexing table

Many of these machines can be equipped with automatic loading and unloading mechanism. Hydraulic control to the drill heads enables fast advance and withdrawal motions to save considerable time over that taken when they have to be carried out at the same speed as the cutting feeds.

Automatic and Continuous Indexing Table Type Machines have been designed to perform secondary operations on small components produced by automatic bar lathes, presses, etc. They are often as fast or faster than automatic lathes, and up to 40 or 50 pieces per minute can be dealt with, each receiving several operations.

Usually there is a fixed drilling head with several spindles, and an indexed table to give up to 12 stations. A jig is fixed to the table and takes up to 12 components arranged to complete the circle. A feed mechanism is interlocked with the drill spindle, so that feeding takes place while the table is stationary and the drill working. The processes which can operate simultaneously include drilling, reaming, tapping or screwing, facing, and counterboring.

Fig. 5.12. Automatic and continuous indexing table type machine

(*Jones & Shipman Ltd.*)

The machine in Fig. 5.12 is set up for drilling 4 holes in brass components, and it is capable of producing 2000 to 3000 per hour. The feeding device is on the left, and on the right is an automatic unloader which ejects the finished parts.

Turret Type Machines have, in place of a normal spindle bracket, a turret similar to that of the capstan lathe, but holding the tools (usually six) in the vertical plane. It can be indexed to bring into operation each tool in correct sequence. Whereas in a lathe the tool is stationary and the work is revolved, here the tool position changes and the work remains stationary, while only the spindle in the bottom position or working station operates. The turret indexing is controlled by a lever which operates an indexing plunger and is also coupled to a driving clutch. As the turret is indexed and the appropriate spindle is brought into position, the plunger lever is released, and as soon as the plunger is correctly located the driving clutch engages and the spindle revolves. Conversely, when the index lever withdraws the clutch, the spindle is stopped.

This type of machine for some time declined in popularity because an efficient type of quick-change chuck was developed, which made tool-changing on a standard machine almost as quick as indexing a turret. The revival in interest is probably due to two features useful with unskilled operators: the tools are always presented in correct sequence, and the revolving stop turret coupled to the tool turret controls the depth of feed independently for each spindle.

TRANSFER TYPE MACHINES, usually designed for special purposes, permit work to be transferred automatically to others for further operations. The layout may include milling, honing and similar operations in addition to drilling and tapping, but invariably the majority of machines are concerned with these last operations. They have been used in the motor industry for many years and their use is now being widely extended.

The complete group of machines is controlled by electric, hydraulic or pneumatic systems, combinations of signal lights on a master panel indicating the progress and completion of various movements. Each machine is set to perform its allotted operation and having completed it, sends to the master control a signal, visibly recorded by a light. As soon as every machine has signalled completion, the fixture carrying the work is transferred complete to the next machine. To ensure correct alignment, each machine locates the fixture by the same method, usually a master plunger, or bushes and locating buttons.

The transfer is by some form of conveyor track carrying a pawl which engages a portion of the fixture, moves it forward to the required position, and then drops away to return to its starting point. It is often possible to arrange a circular layout, so that one operator can unload finished and load up fresh components at the same station. Various devices for automatic inspection are needed at critical positions, or serious trouble can arise. They can be arranged to signal on the master control where a fault has occurred and automatically stop the machines.

The cost of such installations is high, but where continuous production at a given rate is essential, it can easily be recovered.

First-class maintenance, accurate tool setting and renewal of tools in good time are all most important; dislocation due to a fault can be so serious that it is normal to carry a reserve of components and machines.

Deep-hole Drilling. The drilling of deep holes presents the greatest difficulty and a special technique has been evolved. A *deep* hole is one which is long in comparison to its diameter; the oil holes required for pumping oil through crankshafts in internal combustion engines form a good example; also gear-box shafts which often have to be drilled to allow operating rods to work through them. A crankshaft is usually produced by a forging process, and, in spite of careful annealing, there is bound to be some variation of metal structure in the core metal; variations in hardness form one of the problems of drilling and for deep holes careful drilling is required.

One method is to feed the drill at the best rate for the metal being drilled; this means that the feed will not be uniform. Hand feeding is often resorted to, as the experienced operator can feel how the drill is going, and vary the feed accordingly. More recent developments consist of either hydraulic or electronic controls which vary the feed according to the work the drill is doing.

Long drills, which are obtainable for this purpose, may tend to wander or deviate from a straight line. This is specially awkward when some form of twist or push-rod operates through the hole, as in the case of a gear-box shaft. Drilling half-way from each end is not recommended, as accurate alignment is difficult to attain. A satisfactory system is to revolve the work while the drilling is in progress—the work revolving much slower than the drill. It is best to drill horizontally; *horizontal deep-hole drilling machines* with *revolving chucks* can be obtained for this purpose.

Special Attachments. When a batch of components requires to be drilled with holes at reasonably accurate centres to facilitate interchangeability, but the quantity is not sufficient to warrant the cost of a jig or fixture, it is usual to make a template either for marking out the holes or possibly drilling direct. In the former case extra time must be allowed and in the latter direct drilling is seldom satisfactory owing to difficulty of accurate location and to wear. A compound table can be used, but for wide movements, operation of screws controlling them is very tedious.

The special table (Fig. 5.13) developed for such conditions can be adapted to a standard drilling machine provided the throat capacity, i.e. the distance from the centre of the spindle to the capacity, i.e. the distance from the centre of the spindle to the column face, is sufficient to cover the largest backward and forward movement required. In general it follows the principles of a normal compound table, but no screws are included. Both the upper table and the cross saddle are mounted on ball-bearing runners. The length of the top working table however is double that of the normal table as it is divided into sections, one to hold the work and the other for locating the spacing bars. Over the latter portion it will

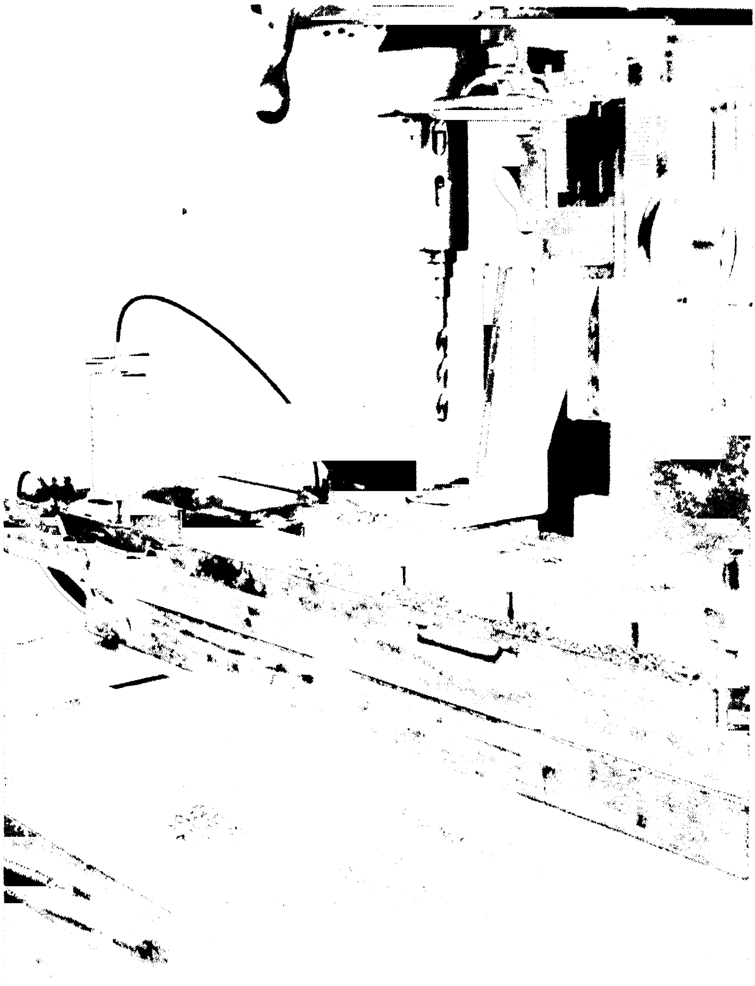


Fig. 5.13

be noted is mounted a bracket carrying a plunger. This is fixed at a known distance from the drilling spindle, and on the table top at the same distance apart are two master edges or datum lines. Work is mounted on the table either touching the master edge or at some specified distance from it, and on the left-hand portion is mounted a plate or bars in which holes at the required centres have been accurately bored. The table is then moved until one hole on the locating plate is in line with the plunger. This is released, enters the hole and correctly locates the component for drilling the first hole. It is then withdrawn and the table moved until the next hole is in line and so on. Table and slide move very freely by two handles, against one of which is arranged a small lever which by a flexible cable withdraws the locating plunger. Workpieces on the table must of course be located by stops at the same distance from the datum edges.

Some further reference, with illustrations, to milling and drilling fixtures, boring jigs etc, will be found in Chapter XXI on Production Engineering.

For Bibliography see end of book.

CHAPTER VI

BROACHING

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Characteristics. Broaching consists of the removal of material by pushing or pulling across the surface to be machined a tool called a broach (Figs. 6.1, 6.2) having a number of teeth or cutting edges which successively engage the work and which generally complete the shaping operation in a single traverse. The cutting speed is relatively slow and the force comparatively large. As the broach moves across the surface, a chip of the material is removed by each tooth until the last few teeth are reached, these being the exact shape or form which is required. A broach may be flat or contoured and may be internal or external. As there is practically no limit to the shapes which can be formed by this process, it is ideal for contours which would be difficult to machine by any other method; e.g. the bores of gear-wheels which are intended to work on a splined shaft, or square and hexagon or irregular-shaped holes in castings and forgings. The main advantages are the accurate machining of intricate contours in a single operation and with long tool life. The appearance of the machines may be seen from Figs. 6.7 and 6.8.

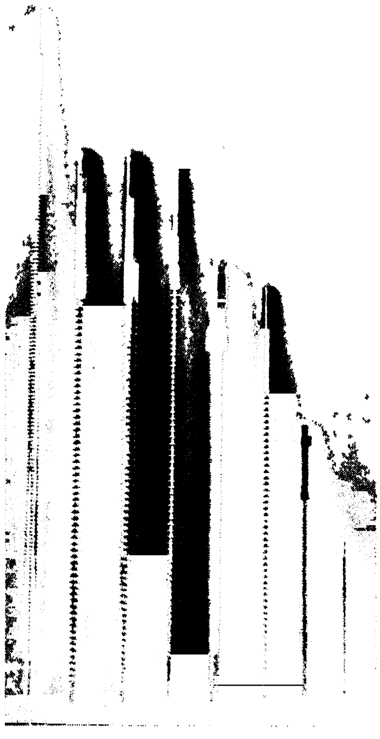


Fig. 6.1. Internal Broaches

Broaching was used in the U.S.A. as early as 1853 and during the Civil War, 1861–5. About the same time, an adaptable type of hand broach was developed in this country, mainly for sizing gun barrels. A patent was granted about 1870 for a multi-tooth cutter-bar for producing keyways and in 1873 the word broaching appears in connection with a broaching machine improvement due to A. P. Stephenson. These early developments were mainly connected with internal broaching (e.g. cutting keyways in the bores of pulleys and gear-wheels); but in 1888 surface or external broaching was accepted as a valuable process for finishing wrenches, etc., this again being the subject of a patent.

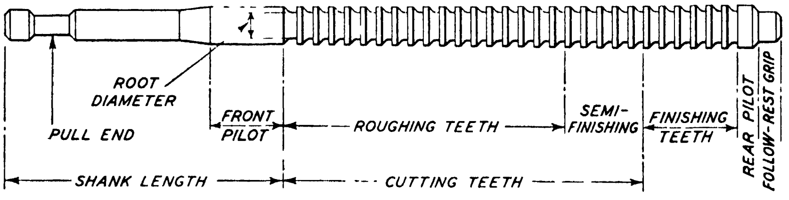


Fig. 6.2. Typical one-pass internal broach

Broach Design. Broaches may be classified in several different ways, namely: (1) *Type of movement*—Push or pull; (2) *Type of operation*—Internal or external; (3) *Construction*—Solid, built-up, or inserted tooth; (4) *Purpose*--Production of hole, spline, serration, or combination of these; spiral or rifling; surface broaching, etc.

Most internal broaches are of pull type, particularly where broaching machines are used, the component frequently being completed in one pass by one broach only. Internal push broaches are useful for sizing operations, and can be used where presses of comparatively short stroke only are available. Compared with pull broaches, the stock removal per broach is small. A good example of the use of push broaches is in sizing, correcting, or burnishing holes in previously heat-treated components such as gears.

The essential features of a broach (Fig. 6.2) are a pull or push end, entering pilot, roughing teeth, semi-finishing teeth, and finishing teeth--the latter when fine tolerances and very high finish are called for, being sometimes followed by burnishers.

It is desirable, and often necessary—other than with finishing teeth—to break up the continuous cutting edge of the broach teeth so as to reduce the width of chip, minimize the risk of chip crowding and reduce the force required. It is important that such breaks be staggered in successive teeth.

With heavy horizontal broaches, a following pilot or grip diameter is necessary as support for the weight of the broach, or as a guide, and this usually leaves the support after the last finishing tooth has passed through the workpiece. A following pilot or guide is also used on vertical internal broaches, particularly where automatic broach handling is fitted.

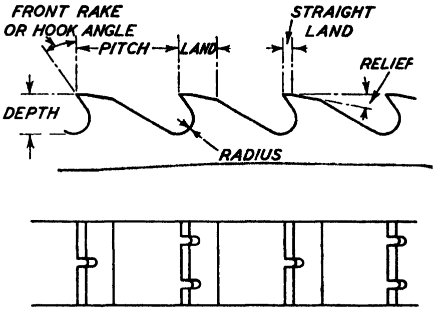


Fig. 6.3. (*Above*) Broach teeth details. (*Below*) Plan diagram showing staggered arrangement of chip-breaker nicks

The number of roughing teeth depends on the material to be cut and the amount of stock to be removed; the number of intermediate teeth on the material and finish required, and of finishing teeth on length of workpiece, and finish and accuracy required. The important elements of tooth design (Fig. 6.3) are:

Front Rake or Hook Angle, governed by the hardness and kind of material in the workpiece; varying from about 6° for cast-iron or hard steel, to 20° for very soft steel, while aluminium and its alloys may require about 10°. For hard brass the front rake may vary from 5° through zero to as much as 5° negative.

Pitch, dependent upon the length of the component to be broached, the material, and the size of chip removed, a good approximation being based on the formula: Pitch $= 0{\cdot}35\sqrt{\text{length of cut}}$. In this connection it should be remembered that components of shallow depth may often be stacked with advantage.

Straight Land which should be kept as short as possible consistent with allowance for prolonging the life of the tooth ~~by re~~grinding the front face. Generally, it should be of a length of 0·01 in. to 0·02 in. in the roughing teeth, but may decrease to as little as 0·005 in. in the finishing teeth. Some slight backing-off of the straight land is necessary, again varying between the roughing and finishing teeth; for the former it might be from ½° to 1°. If left quite parallel there is always a danger of this becoming negative due to frictional load.

Land, the total width of tooth including straight land and relief.

Relief, the clearance behind the straight land to give maximum support without imposing any frictional load.

Radius, which is extremely important and causes the chip to curl, preventing it from crowding in the tooth space.

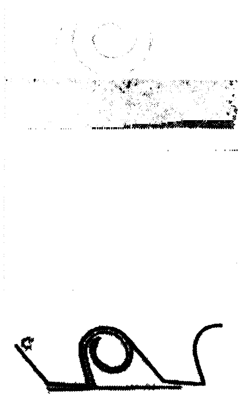


Fig. 6.4. Chip formation on broaching (× 2)

Depth of Tooth, governed by the pitch and chip space required and sufficient to prevent any crowding of swarf.

A correctly formed steel chip is shown at the top of Fig. 6.4. In the middle can be seen the effect of insufficient tooth spacing, resulting in the breaking up of the chip, crowding and possible breakage of the broach teeth. The sketch at the bottom shows the chip in the act of forming, and clearly illustrates the importance of the root radius in chip formation.

Surface Broaches. Typical surface broaches or inserts, are illustrated in Fig. 6.5 and are usually made up in short sections 8 in. to 12 in. long, for three reasons: ease and cheapness of replacement, increased scope for efficient design of the work, and ease of manufacture and control during heat-treatment.

The chip breakers on the radii of the first section are important, as there is always a tendency for chip crowding in broaches of this type. In the second example suitable breakers are seen in a broach which has a straight face.

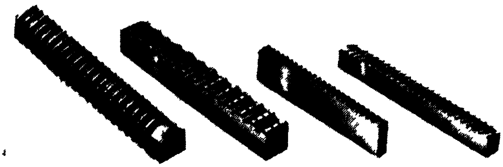


Fig. 6.5. Surface broaches and inserts

Blades such as those illustrated are usually held in sub-bars which, when of a composite character, are further assembled into main bars which are bolted direct to the machine slide This allows either a single insert or the complete tool outfit to be removed quickly from the machine, and replaced by a duplicate, ensuring continuity of production.

In general, it may be said that the tooth characteristics of surface broaches are similar to those which have been considered in relation to internal broaches, except that chip-breaker grooves are probably more necessary in the latter. In a surface broach, the use of tungsten-carbide inserts, forming a short section for sizing and finishing, often considerably increases the life of the broach, whilst maintaining accuracy for longer periods.

Reaction Slides. It should be noted that when broaching regular-shaped holes, the cutting reaction is balanced due to the contact of the broach round the hole. With, however, surface broaching, the cutting reaction is on one side of the broach only and this has to be counteracted by some form of slide on the opposite side. This point must be taken into consideration in all cases where the cutting reaction is unbalanced.

Cutting Speeds. These vary over a wide range and in general should be kept as high as possible, consistent with the particular conditions. Most mild steel, cast iron, and brass can be machined up to 25 ft./min., while on the other hand, some of the higher tensile alloys may require speeds as low as 3 to 4 ft./min. for satisfactory finish and long tool life. Aluminium and magnesium should be cut as fast as possible, due allowance being made for any alloying constituents. The modern hydraulically operated broaching machine permits wide and easy speed adjustment. A valuable feature incorporated in some hydraulic machines is a variable two-speed cutting cycle. The roughing portion of the cycle can be made at high speed which automatically drops for the finishing portion of the stroke, the change being effected without interrupting the cutting operation.

The shock experienced by each tooth as it meets the workpiece must not be forgotten, particularly with regard to the fatigue strength of the broach.

Coolant. As in all machining operations, the coolant in broaching keeps the tool temperature down while cutting, and acts as a lubricant to the cutting face and helps in the disposal of the chips. It may be taken as an axiom that the heavier the cut the greater the viscosity of the fluid required, and internal broaching normally calls for a more viscous fluid than external. The usual straight oils and soluble oils can be used, and sometimes a dilution of the former by paraffin may improve results. The best cutting oils for broaching are those known as sulphurized, and several lubricant suppliers now market this type. With steels in the lower tensile range, and for brass and aluminium, a soluble base oil suitably diluted is best. Cast iron can usually be cut dry, but in some circumstances a very light oil, or soluble oil, may be used with a mixture of paraffin, if high finish is important; though more frequent regrinding will then be necessary.

The volume and direction of the coolant are also important factors, as the tool must be completely and heavily flooded as close as possible to its points of contact with the workpiece. This is more easily dealt with on vertical machines than on the horizontal type. It is of course important that the coolant be kept clean by efficient filtering, as foreign bodies, such as fine chips or grinding dust, may damage not only the broach teeth but also the machine ways.

Advantages and Limitations of Broaching. In engineering practice, it is generally easier to produce accurate external than internal forms, particularly where hardening and grinding are involved. The internal broach, itself formed externally, is comparatively easy to manufacture, and once produced continues to reproduce its form over long periods of use; it is easily reconditioned when its cutting edges are dulled; and the accuracy of the final product is maintained, because only the few finishing teeth need to be of exact size and form necessary, and these are not subjected to the same hard usage met with in other machining methods. The fact that different roughing and finishing teeth can be combined in one set-up is obviously an advantage, and generally allows of faster stock removal than other metal-cutting processes. Individual cutting teeth only being in contact with the work for such a brief period, removing a predetermined and relatively small amount of stock, there is a minimum of frictional resistance and consequent heat absorption. The maintenance of dimensional accuracy and tolerance has already been referred to, other advantages being the high finish obtainable, and the fact that combined machining operations—for instance, internal and surface broaching, or machining in different planes in correct dimensional relation to each other—can be performed.

The limitations of the technique include its unsuitability for large stock removal, the fact that it is not applicable where there is any obstruction to the passage of the broach in relation to the workpiece (although suitable design will often obviate this), and its often uneconomic character where only small total production is called for. On the other hand, even for small quantities, it is the cheapest technique in certain cases, examples being regular or irregular-shaped holes, spline, or spiral spline holes and serrations. In surface broaching the capital cost of the machine and equipment is a more likely deterrent than the tooling expense. The use of two broaches working simultaneously and in directions inclined to each other now enables taper work to be produced.

Broaching Machines may be classified according to direction of operation:

1. *Horizontal (hydraulic or mechanical operation):*
   (*a*) Single ram (or screw); (*b*) Duplex ram (or screw); (*c*) Drum or turret; (*d*) Special—mostly surface broaching or rifling.

2. *Vertical (hydraulic operation):*

Internal	*Surface*	*Combination*
(*a*) Pull up.	(*a*) Single slide. (1) Fixed work-table. (2) Shuttle work-table.	Two-way and three-way machines may be used as pull down internal or slide type surface with fixed table.
(*b*) Pull down.	(*b*) Duplex slide. Shuttle work-tables alternating with broach slides.	
(*c*) Push down.		

Fig. 6.6. Workhead of horizontal broaching machine

Fig. 6.6 shows the workhead of a horizontal machine on which a 10-spline broach is being pulled through the workpiece. At the right, behind the workhead may be seen the broach puller which is operated by a hydraulic cylinder. The pull-head, which is supported on hardened and ground steel ways, has vertical adjustment by an elevating screw, the star knob of which is visible. The broach in this case is of some length, and is therefore supported on a similar crosshead, working on hardened and ground ways, which are seen on the left. This second crosshead (not shown) is held by a stop shortly before the broach reaches the end of its stroke, so that the rear end of the broach may leave the crosshead and pass freely through the workpiece. Auxiliary bushings may easily be fitted in the workhead according to workpiece requirements.

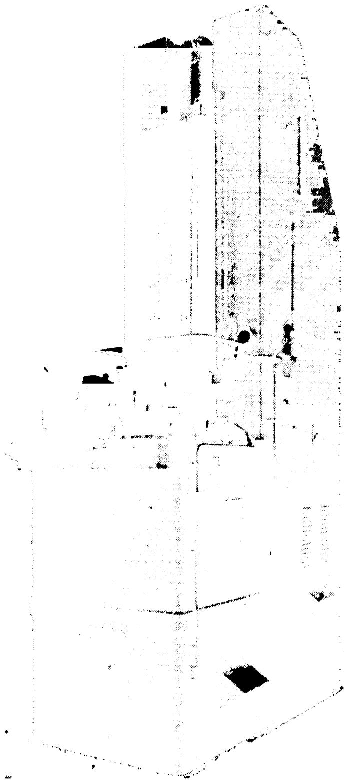


Fig. 6.7. Vertical single-slide hydraulic surface broaching machine with H.S.S. insert broaches

The vertical surface broaching machine in Fig. 6.7 has 15 ton capacity and 66″ stroke. A reciprocating worktable automatically moves to and from the broach slide and is synchronized with it to facilitate loading, and to permit the free return of the broach slide.

In the horizontal machine in Fig. 6.8, the broach inserts are of tungsten carbide, allowing of greatly increased cutting speed.

Reference to cutting speeds has been made on page 167 relative to screw or hydraulically operated machines, but recently there have been considerable developments in the design of high-production surface broaching machines with electro-mechanical drives, working at speeds as high as 300 feet per minute, using both high-speed and tungsten-carbide broach inserts. Such speeds are impracticable with hydraulically operated machines.

Another recent development, adapted more generally to horizontal machines (but which is also being applied to vertical) is modelled on the lines of a continuous chain, carrying a number of identical work-holding fixtures which pass, in turn, contacting the broach inserts supported in a fixed broach holder. During the passage of the work-holding fixtures over the broaches they are, of course, rigidly held in suitable slideways.

Machine Selection. First, the length of stroke required must be established. This will be governed by the maximum stock removal, the rise per tooth, tooth pitch, and length of component. To the dimension obtained must be added sufficient to clear components and fixtures. The number of broaches to be used simultaneously in internal broaching, or the choice of single or duplex slides in surface broaching, will depend on output required and the number of separate operations to be performed. Having determined these, the required load of the machine can be established.

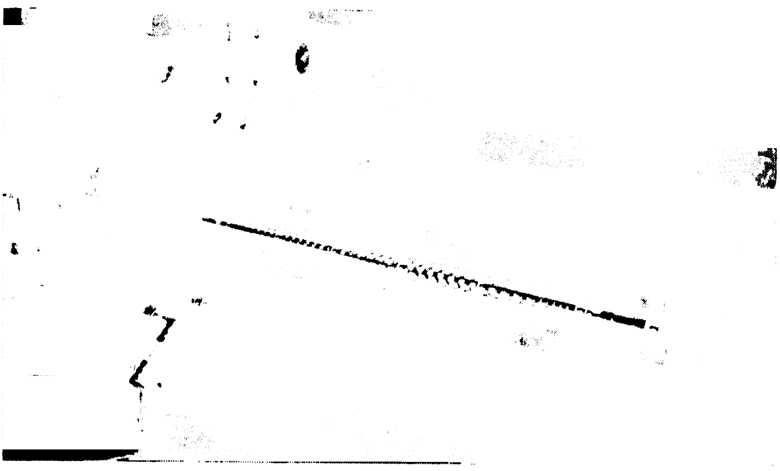


Fig. 6.8. Horizontal single-slide hydraulic broaching machine with tungsten carbide insert broaches

A formula for arriving at this maximum load required in 100,000 *pounds units* is:

$$L = N \times C \times W \times K$$

where N = number of teeth cutting at one time, C = thickness of chip per tooth, W = width of face, and K is a constant depending on the size of chip and the nature of the material. The values of the constant K can be obtained by reference to the graph (Fig. 6.9). It will be seen that increase of chip thickness does not give a proportionate increase of load, and that this is particularly the case for chips of less than 0·005 in. For internal broaching the value of W will be the total length of the periphery.

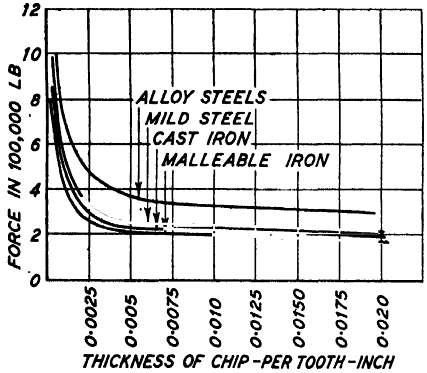


Fig. 6.9. Machine load capacity: curves showing values of constant K for various materials

It is important that the capacity of a broaching machine should be more than the minimum required to carry out the work efficiently; otherwise an increased number of broaches, used in succession, may be required to avoid overloading. The extra capital cost of increased power or length of stroke is not usually excessive.

For Bibliography see end of book.

CHAPTER VII

SHAPING, PLANING AND SLOTTING

By J. V. BRITTAIN, B.Sc. (Eng.), A.M.I.E.E.

Characteristics. This group of machines is designed to generate flat surfaces by means of one or more single-point cutting tools. During the cutting operation the relative motion between the tool and the work is in a straight line, the three machines differing according to whether the motion is horizontal or vertical and whether the moving part is the cutter or the work. After each cutting stroke the relative motion of tool and work is reversed and a small relative movement at right angles to this is imparted, to provide the "feed" for the succeeding stroke. In a *shaper* the work is stationary during cutting, while the tool reciprocates, the cut being taken in one direction only while the feed is normally provided by moving the work. A *planer* operates in the converse manner: the table on which the work is fixed moves backwards and forwards and the cutter is stationary. In both, the cutting motion is horizontal. With a shaping machine it is not usual to use more than one cutter but a planing machine is often fitted with twin tool-rests enabling two independent cuts to be taken, or two pieces of work to be machined at one time.

A *slotter* operates in a similar manner to a shaper except that the cutting motion of the tool is vertical. The work table is horizontal, and can be given a rotary motion for machining a circular periphery or internal bore. This is often required where the curved portion is not a whole circle and thus not suitable for machining on a lathe.

In general these three machines are used more for unit or batch than for quantity production. Compared with other machine tools, their rate of metal removal is slow, due to inertia and the time lost owing to the use of a reciprocating motion, so that a high finish, such as is obtained by turning at high speeds and with fine feeds, is not attempted. They are, however, very versatile and many unusual operations can be carried out on them. All general-engineering shops have one or more of each type of machine, and the three types together enable a wide variety of work to be done.

The planer will deal with much larger workpieces and will machine much larger surfaces than the other two machines. A miniature planer, of which there are many in use, may not deal with work of greater bulk than that which can be handled on a normal shaper, but can operate longitudinally on any part of a workpiece much too long to be accommodated in a shaper.

Driving Systems are of varying types and must give a quick return to save working time. The cutting speed is slow but should be variable. Early models provided a range of three or four cutting speeds by means of cone pulleys, but all modern machines have gear control if the drive is purely mechanical. For shapers and slotters the motion is usually by some form of crank device but certain heavy-duty shapers are operated hydraulically, giving a wide control of speed. For planers the drive is by rack and pinion or by spiral (screw and nut) arrangement.

The wider range of cutting speeds now required was originally provided, mainly on planers, by an electrical control such as the Ward Leonard system. Here the machine is driven by a D.C. motor supplied by a D.C. generator coupled to the main driving motor. This gives accurate and easy control by altering the excitation of the D.C. generator, and has become standard on most medium and heavy-duty planers. Electronic controls may replace the rotating units but the principle will be virtually the same. These controls are costly, whether large or small, and are thus confined to the more expensive machines.

Cut and Feed. The earlier shapers had stationary or fixed work tables and the reciprocating head travelled sideways across the work to give the feed. This type is still in use but has largely been supplanted by the modern type in which the reciprocating head has no sideways motion, the feed being obtained by moving the work table. In both cases the depth of cut is provided by an additional slide, mounted on the end of the "ram" and carrying the tool-post. With the slotter both feed and cut are obtained by moving the work table.

In a planer, the cut and feed are obtained either by moving the toolholder across the work table, or by moving the cross-bar carrying the toolholder or toolholders, up or down; according to whether the face to be machined is horizontal or vertical.

Some Typical Shapers

Fixed Head Crank Shaper. This is the normal type for both production and tool-room work (Fig. 7.1). It will be seen that the

Fig. 7.1. Fixed head crank shaper (*Butler Machine Tool Co. Ltd.*)

feed is obtained by moving the table horizontally, the cut being controlled by the tool-head. The operation of the ram on such a pillar-type shaper is through a slotted link motion, the principle of which will be seen in Fig. 7.2. It is inevitable with this mechanism that the velocity of the tool will vary throughout both the forward and return stroke, and the velocity diagram is given for the particular size of link and

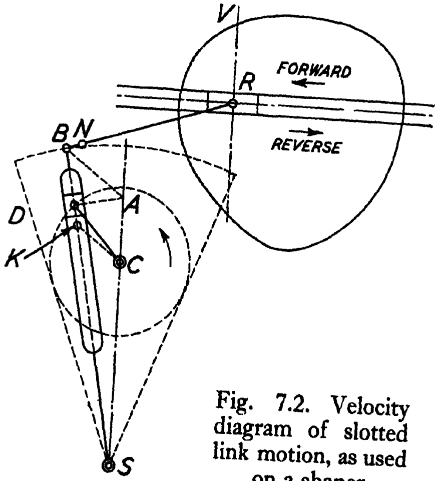


Fig. 7.2. Velocity diagram of slotted link motion, as used on a shaper

crank figured. The ordinate RV represents the cutting speed on the forward stroke when the ram is in the position shown. To obtain the velocity curve the line DA is drawn at right-angles to the slot and AB joined. CK is then drawn parallel to AB, and the vertical KN then represents the velocity which is plotted at RV. The scale is given by the fact that the length CD represents the linear velocity of the crank pin D. This arrangement gives the desired quick return, and is very convenient for varying the stroke. The number of strokes per minute is controlled by the drive, and the actual cutting speed will thus vary with the stroke for any given number of strokes per minute.

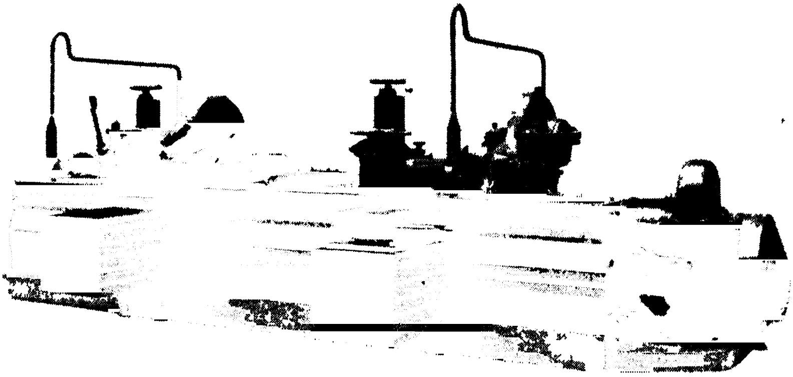


Fig. 7.3. Travelling head shaper with two heads and two tables.
(*Butler Machine Tool Co. Ltd.*)

Travelling Head Shaper. Here the reciprocating ram which carries the tool-slide is itself mounted on a saddle which travels sideways along the bed. The general arrangement will be seen from Fig. 7.3, and it will be realized that large or massive workpieces can be more conveniently held in position on this machine than on a pillar-type shaper. If necessary the work can be bolted to the floor instead of to one of the tables. Where there are two tables, one piece of work may be prepared on the spare table while another is being machined. The Whitworth quick-return motion is very suitable for this type of shaper although the slotted link may be used.

The cut is obtained by means of the tool-slide, and the feed by moving the sliding head along the bed, this motion being arranged by driving a screw through a ratchet with suitable gearing to vary the feed. The feed operates at the end of the return stroke when the tool is free from the work. When machining vertical surfaces the feed is provided by the vertical slide and the cut by the sliding head. A further refinement is the addition of an automatic vertical feed to the tool-slide. Hydraulic cylinders may be used to give the reciprocating motion, the ram being connected directly to the piston and the length and position of the stroke controlled by dogs attached to the ram. The hydraulic power is provided by a self-contained pump and motor. One advantage of this type is that the cutting speed can be kept reasonably constant throughout the stroke, thus giving a better finish and avoiding the ripple marks which are difficult to avoid with a gear-driven machine, particularly when the machine is set for long strokes. Hydraulic shapers are expensive and are usually employed on tool-room and similar work where their special advantages are required.

Draw-cut Shapers cut on the return instead of the outgoing stroke, thus giving, compared with the normal type, a more perfectly controlled cut (cf. the difference between the actions of a chisel and a spokeshave). They are heavily built units and for large castings may be taken to the work and fixed to the floor. Struts, suitably disposed, are often incorporated to help to carry the heavy pressures involved.

Planers are essentially for machining plane surfaces which are larger than can be cut or reached on the shaper. Although small machines are manufactured, planers are usually fairly large heavy-duty units for rapid roughing and finishing of such work as engine or lathe beds, etc. The modern planer (Fig. 7.4) with modern electric controls has a much higher output than its predecessor.

The planer has a reciprocating table which travels beneath a cross-bar on which the tool-heads are mounted. Normally one or two tool-heads are mounted on the cross-bar, but additional tools, generally for cutting vertical faces, may be mounted on the columns supporting the cross-bar.

The usual design comprises two vertical columns between which the table reciprocates, the cross-bar being mounted to slide vertically on these columns. All motions for feed or cut take place either by dropping the cross-bar, moving the tool-head across the cross-bar, or lowering the tool-holder mounted on the tool-head. The first two of these motions are generally power or hand operated but the last is often hand operated only.

The table is normally operated by some form of rack and pinion or spiral drive; an example is seen in Fig. 7.5.

A quick return is essential for high output and in earlier planers this was obtained by using two belts, for the forward and reverse drives, with the reverse motion at a higher speed. The arrangement gave only one cutting speed unless a cone-pulley countershaft was employed, and the lack of speed control was a disadvantage. Modern high-speed planers are now fully electrified.

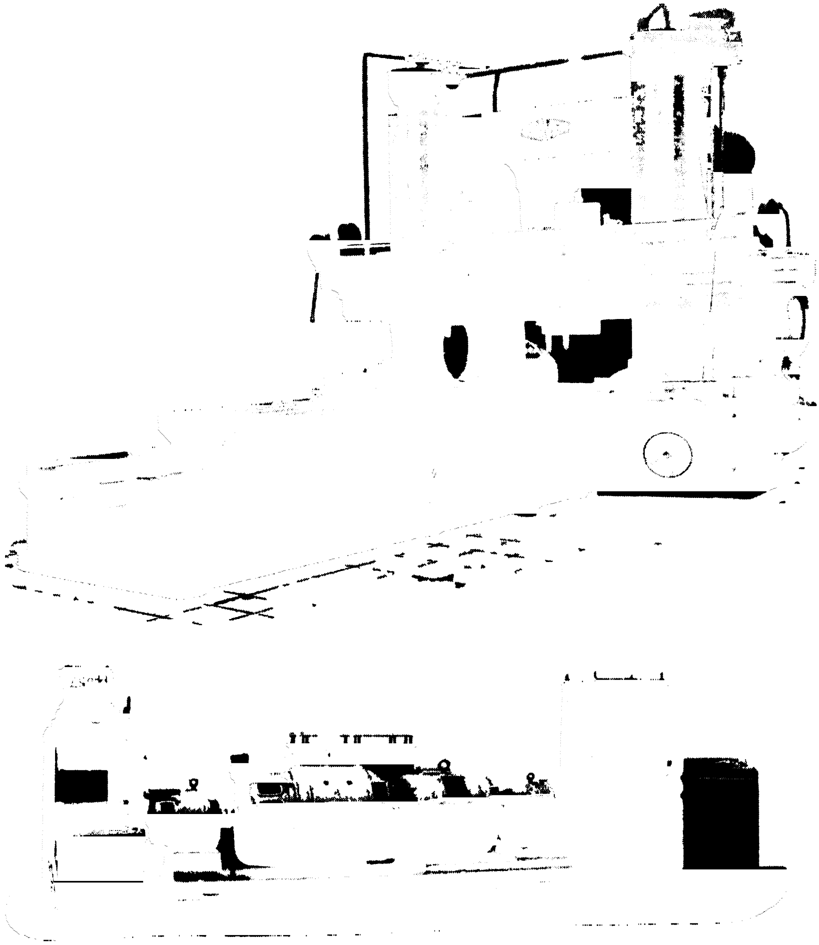


Fig. 7.4. Electrically-operated planer fitted with four tool-heads. (*Below*) Electrical motor-generator set for driving the motor (*Craven Bros.*)

Electric control and operation has done much to speed up output. The drive for the table is by a motor mounted on the planer, supplied by a special motor-generator set operating on some variation of the Ward Leonard principle. This enables heavy cutting pressures to be dealt with and quick reversals to be obtained without very heavy switchgear. Very smooth running under full control of the operator is obtained. The electrical unit and control gear of such a planer is seen in Fig. 7.4, the operating panel being on the right.

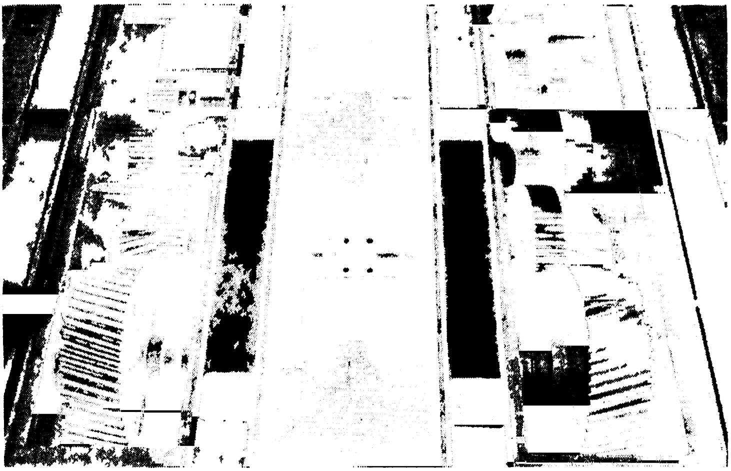


Fig. 7.5. Drive for a gear-driven planer, exposed by removal of table (*Craven Bros.*)

An *Open Side Planer* has only one vertical column and this allows large castings, etc., to be mounted on the table and to overhang on the opposite side to the column. A *Rail Planer* is specially designed for machining rails for points and crossings and is a light machine with a narrow table but arranged to accommodate long lengths. *Tandem Planers* have two tables operating on the same bed. This arrangement enables one table to be loaded while the other is in operation, or it is possible for the two to be coupled together for a large workpiece.

THE CLAPPER BOX. As in planers and shapers the action is a reciprocating one; the tool must follow the same track on the return as on the forward motion. This means that some relief must be given to the tool so that it does not rub on the return journey. The usual arrangement is to have a hinged tool-post as in Figs. 7.6 and 7.7.

The clapper box is usually arranged to pivot laterally up to about 20° so that the relieving action can be obtained when machining vertical faces (Fig. 7.6). A solenoid may be used to lift the tool completely clear of the work on the return stroke.

Recent refinements fitted to shapers provide more accurate working and more delicate control, particularly for tool-room work. They include multi-disc friction clutches, flywheels to give smoother running, cam-operated feed adjustment and single lever controls for speed variation.

Tools for Shapers and Planers are usually sturdier than lathe tools owing to the need to withstand the impact load at the commencement of the cutting stroke as well as the heavy cut often employed and the frequent need for considerable overhang. As the motion is in a straight line, the top rake is also less than with lathe tools.

It is important to guard against "digging in" which may be caused by the softness of the material or by hard patches. This may be avoided by using a cranked tool with the cutting edge *behind* the centre of the hinge of the clapper box (Fig. 7.7). A tool shaped like the one on the left, with the cutting edge in front of the centre will tend to dig into the work whereas with the tool on the right any spring of the tool would take the cutting edge out of the metal.

Standard shapes for general-purpose work include right and left-hand roughing tools, right and left-hand finishing tools, and straight-nosed and round-nosed grooving tools. Cutting rakes depend upon the material used and are mostly almost zero for cast brass and gunmetal; 5° positive for cast iron and cast bronze; 6° to 10° positive for steel, the lower rake angle being used for high-tensile steel and the 10° rake angle for mild steel. Higher rake angles up to 20° are used with light alloys and other ductile materials.

Slotters. The slotting machine may be looked upon as a vertical shaping machine. It will machine the internal surfaces of a casting or forging and can do circular work by virtue of its pivoted table. Originally slotters were used for cutting keyways in the bores of pulleys, etc., and machining the square holes in such parts as dog clutches and they are still used for this work in small shops.

There are two classes of slotters—*Puncher Slotters* for heavy duty and *Precision* or *Production Slotters* for high speeds and fine finishes. Normally the slotter is a general tool and is used for a wide variety of work but production slotters are arranged for the use of jigs, etc., to deal with repetition work.

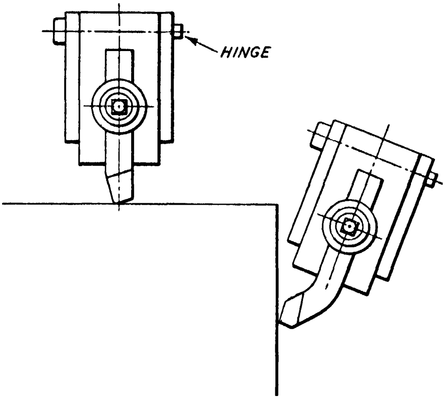
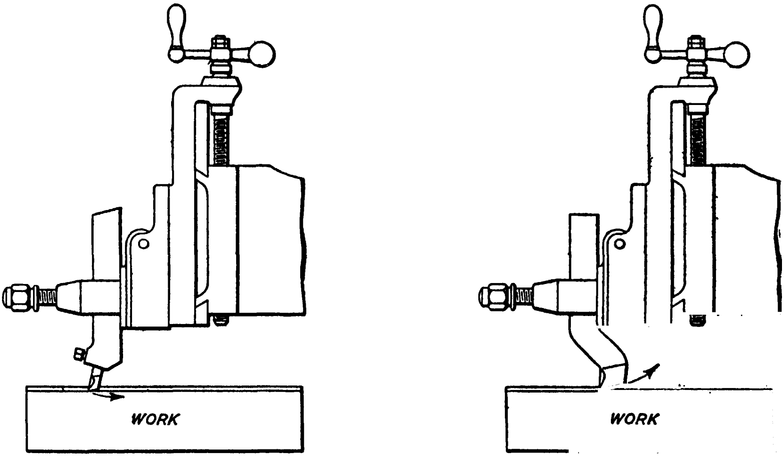


Fig. 7.6. Clapper arrangement as used on a shaper or planer, viewed in the direction of the return stroke when the tool lifts to avoid rubbing



WRONG
LATHE TOOL USED FOR SHAPING WILL DIG INTO WORK

RIGHT
GOOSENECK TOOL WILL SWING OUT OF WORK

Fig. 7.7. Use of cranked tool on shapers and planers to avoid "digging in"

A *tool-room slotter* is shown in Fig. 7.8. It will be seen that the face of the ram is flat and has tee-slots machined in it. There are many different methods of holding the tool, and various forms of tool-holder may be fitted to cope with the wide variety of work which can be done. It is not practicable to fit the normal form of clapper box to a slotter and thus the tool generally "rubs" to a certain extent on the return stroke. Fig. 7.9 illustrates the type of work undertaken by puncher slotters, together with the times taken to remove the metal indicated. This type of slotting machine is extremely useful for profiling holes from the solid. A starting hole is drilled to enable a tool to be used to "nibble" the profile. Up to 4 to 5 lb. of steel per minute can be removed in this type of operation.

The mechanism for driving the vertical ram may be either a rack and pinion, a spiral drive or a simple crank (quick return) action. The simplest is the crank mechanism and this is usually provided on the general-purpose machine. The spiral drive consists of a straight-toothed rack mounted on the ram and operated by a worm driven by a variable-speed reversing electric motor. It is usual to balance the weight of the ram by means of levers or chains carrying a balance weight. The general-purpose slotter is not a high-speed machine as

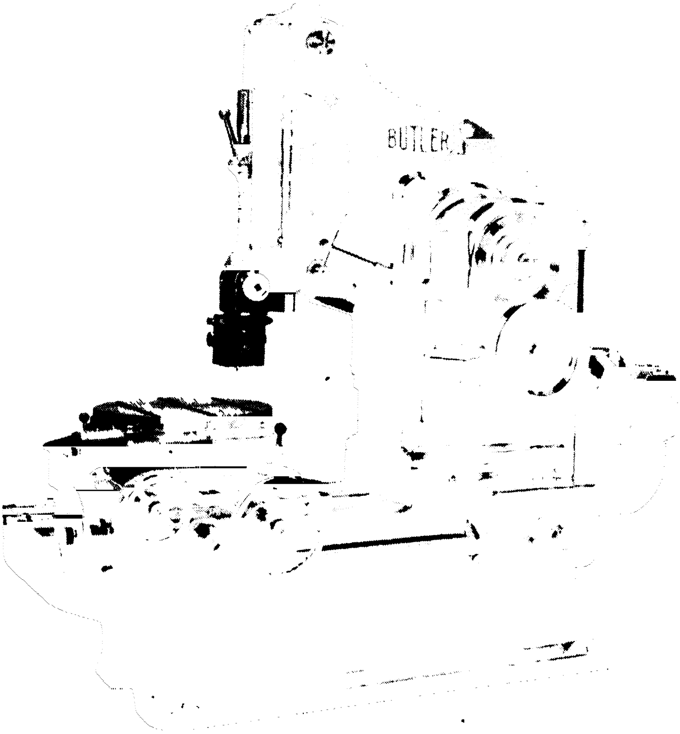


Fig. 7.8. Tool-room slotter for precision work on dies, moulds, etc.
(*Butler Machine Tool Co. Ltd.*)

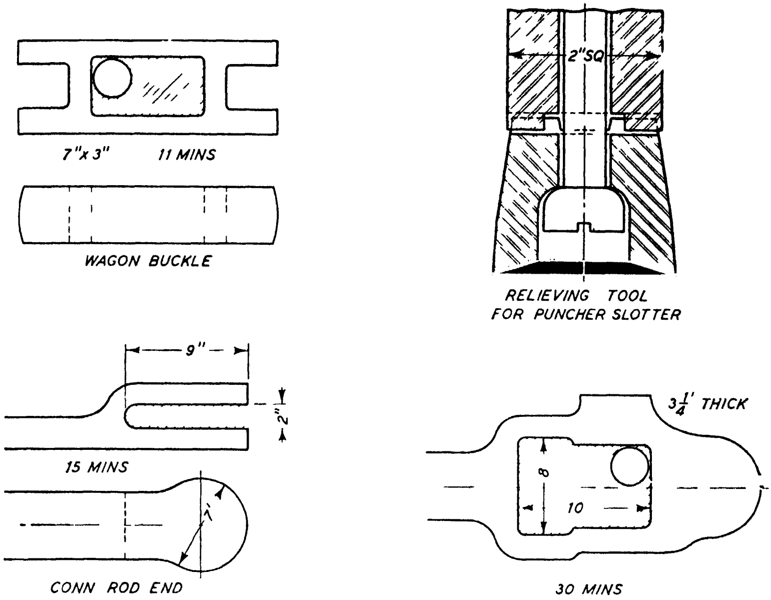


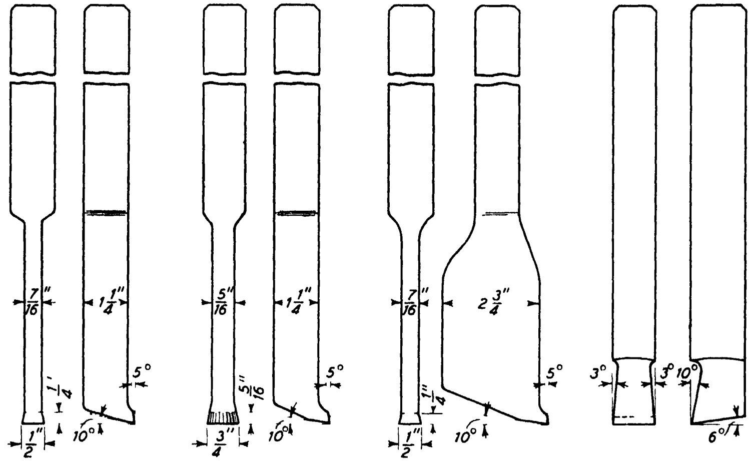
Fig. 7.9. Typical work done on puncher slotters, with times taken

there is considerable inertia in the moving parts, but it will normally take heavy cuts.

Production Slotters are lighter machines for higher speeds and are intended for lighter cuts and more accurate finish. The return (upward) stroke is usually rapid and a special form of clapper toolholder may be fitted. The drive is through a gear-box giving three or four working speeds ranging from 20 to 100 cycles per minute.

Tools for Slotters. The cutting action of slotting differs from planing or shaping, as the end face of the tool is the cutting face. Typical slotting tools are shown in Fig. 7.10. The actual rake angles used are similar to those employed for shaping. Tools of the normal planer type can, of course, be used with special type toolholders, in which case the shapes correspond, but the tools have shorter shanks. This type of tool is used frequently in puncher slotting machines for profiling crank webs or similar work.

Uses for Shapers, Planers and Slotters. Important uses of slotting machines of the quantity production type include the production of keyways in wheel hubs and the machining of irregularly shaped holes. The swifter method of broaching is, however, replacing the slotting machine on mass-production work, in cases



½" KEYWAY TOOL ¾" ROUND NOSE TOOL ½" PARTING TOOL RELIEVING TOOL

Fig. 7.10. Typical slotting tools

where small apertures only are needed. Slotting machines still retain usefulness for small quantities. Similarly, the shaping machine can be replaced for most purposes by the milling machine, where, on account of the use of multi-toothed cutters having a greater continuity of cutting action, a shorter cycle time can be maintained than with the single-point shaper tool. The expensive cutters used with

TABLE 7.1. CUTTING SPEEDS FOR SHAPING OR PLANING DIFFERENT MATERIALS USING HIGH-SPEED STEEL TOOLS

Material to be cut	*Surface speed in ft./min.*
Alloy steel (containing nickel and chromium) .	25–30
Cast iron	30–50
Malleable iron	30–60
Cast steel	30–40
Steel forging (0·15 to 0·2 per cent carbon) . .	30–60
Mild steel (black)	30–65
Mild steel (bright)	40–70
"Yellow" brass	As fast as practicable
"Leaded" brass	" " " "
Cast brass	" " " "
Bronze	40–70

the milling machine, however, and the relatively long setting time involved, still leave the field of small and medium production runs open to the shaping machine. The field of the planing machine has not been encroached upon to such an extent, but here, also, the plano-milling machine is gaining favour, owing to its higher speed of metal removal. Thus, in modern production, the planers, shapers, and slotters have their largest sphere of usefulness in medium quantity production, and in the manufacture of special-purpose equipment, where the short time required for setting, and the extreme cheapness and simplicity of their single-point tools, give the greatest benefits.

For Bibliography see end of book.

CHAPTER VIII

PRECISION GRINDING AND ULTRASONIC MACHINING

Part I: PRECISION GRINDING

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Part I: PRECISION GRINDING

THE precision grinding machine is now one of the most important machine tools, since the accuracy and finish required of well-mating components can best be obtained by its use. If the tolerances necessary to produce the required degree of interchangeability are smaller than 0·005 in., precision grinding machines must nearly always be used.

Grinding-wheels. Grinding-wheels for precision work are made in a great variety of gradings and bondings, and range in size from small points where the abrasive is mounted directly on a small steel spindle, the wheel and spindle being manufactured as a unit, up to wheels of 50 in. in diameter. They are also made in a great variety of widths. There is a British Standard Specification for the diameter of the hole by which the wheel is mounted on the collet, the special chuck for locating it accurately on the spindle.

The method of mounting wheels and collets is important for satisfactory work and for safety. Some compressible material must always be interposed between the flanges of the wheel collet and the sides of the wheel, so that the flanges grip the wheel over the whole area of their faces and especially at the extreme outside diameter. The hole in the wheel must fit the spigot portion of the wheel collet closely, but it must not be tight or the wheel may be burst by expansion of the collet with heat.

ABRASIVE MATERIALS. Grindstones are made of naturally occurring sandstone. Arkansas slips, Water of Ayr, emery, and other abrasives have been used for centuries. Nearly a century ago the use of emery was extended by bonding the emery grains so that grinding-wheels and abrasive sticks and slabs could be formed.

Emery or *Corundum* is naturally-occurring aluminium oxide (Al_2O_3), with many impurities, and usually includes a high percentage of iron oxide. Some emeries contain no more than 75 per cent of corundum and, although bonded grinding-wheels of emery had a far wider use than natural stones because they could cut hardened tool steel, the varying constitution of natural emery made the cutting properties uneven. Today, if the natural corundum in the form of emery only were available, quantity production would be unknown.

In 1891 the first *artificial* abrasive was found more or less accidentally in experiments with small electric furnaces; from a mixture of powdered clay and coke some crystals were produced, which were found to be silicon carbide or *carborundum*, SiC. These crystals were almost as hard as diamond and harder than the natural corundum in emery. Artificial aluminium oxide was later produced by melting bauxite, in which iron borings and ground coke were mixed, in an arc furnace; it was found to be about 95 per cent Al_2O_3 with residues of 3 per cent of titanium oxide, 1·5 per cent of silica, and about 0·5 per cent of iron oxide. Processes were quickly developed for the control of the amount of residues, as it was found that these had a very great effect on the cutting properties of the aluminium oxide and increased its scope as an abrasive. Immediately these new artificial abrasives became available, grinding machines were developed, and the idea of quantity production was realized.

GRITS AND BONDS. Apart from the standard form of corundum, heavy-duty abrasives less liable to crumble are used in wheels for "snagging" or dressing. For grinding glass, and also for lapping, a special high-tempered aluminium oxide is used, and another type for resinoid bondings. A white friable form of aluminium oxide gives a cool cutting action, valuable for tool-room work.

Silicon carbide (carborundum) is also produced in different types: heavy-duty tough black carbide is used for snagging, another special grade for resinoid bondings; and the normal type, which crumbles more easily than the black, for more general purposes.

Some processes need diamond wheels, in which small diamonds are mounted in a matrix.

The usual types of *bonds* are vitreous, silicate, resinoid, rubber, and shellac, the *vitrefied* wheels being the more generally used. Many of the larger size wheels are made in a *silicate* bond, which is also valuable for tool grinding and other operations in which the heat generated must be kept to a minimum. *Resinoid* and *rubber* bonded wheels can be run safely at very high speeds, e.g. 16,000 ft./min. and are particularly valuable when thin wheels are required for cutting-off operations, or where the wheel has to be subjected to lateral strains in the grinding operation; they are very little used in precision work. *Shellac* bonded wheels are used for light duty and certain finishing operations.

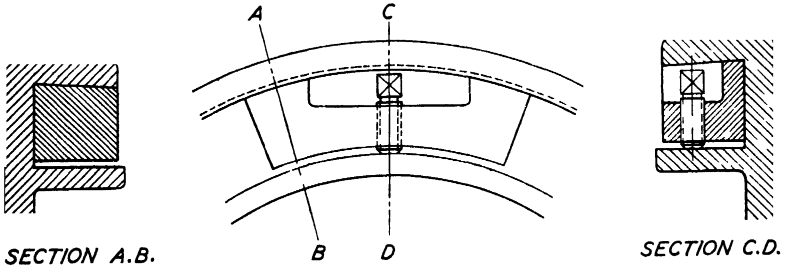


Fig. 8.1. Balancing weights

The structure of the wheel depends on the size of the grit and its spacing. A 60-grit is one which will pass through a silk mesh with 60 strands to the inch, and be retained by a screen having 70 strands per inch. Spacing of the grit is determined by the material to be ground. Soft ductile materials usually require a wide spacing to allow easy penetration, whereas with harder materials close spacing is preferable. In grinding very hard materials, however, such as cemented carbides, which are nearly as hard as the abrasive, an open grain is necessary so that the grit is released freely from the bonding to bring new cutting grains into use.

BALANCING. All grinding-wheels should be balanced except for the smallest sizes. The usual practice is to equip the wheel collets with balancing weights (Fig. 8.1). The wheel collet with wheel mounted in position can be mounted on an arbor made specially for the purpose, the wheel assembly being supported on balancing ways (Fig. 8.2) for the adjustment of the weight. The mounting of the balancing ways directly on the machine serves as an ever-present reminder of the importance of the balancing operation, but this is not always practicable.

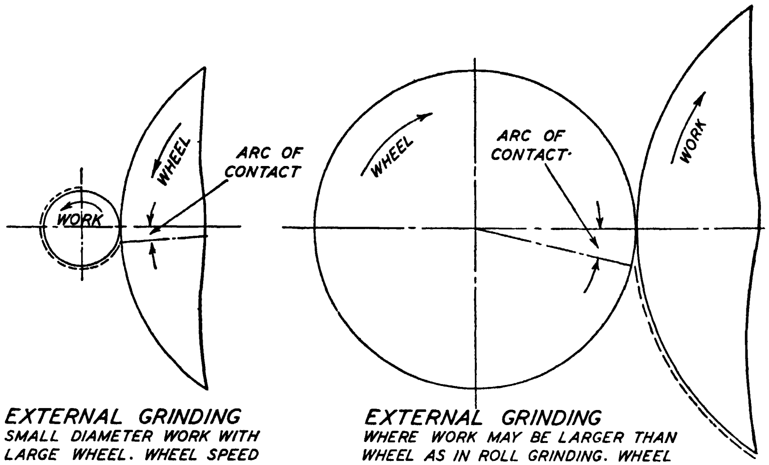
The balancing equipment described gives static balance only. In precision-grinding machines, however, every high-speed rotating part should be dynamically balanced to eliminate vibrations which would directly affect the ground finish obtainable on the work. Present practice limits the balancing of the grinding-wheel assembly to static balancing; there is scope for research work in grinding-wheel manufacture with a view to obtaining such a degree of homogeneity that a grinding-wheel of, say 20 in. diameter and 6 in. of wheel face, would not set up serious dynamic unbalance during any part of its life. The usual static unbalance that occurs on standing wet after use passes off slowly after the machine has been put to use again.

All new grinding-wheels to be mounted in collets should be first tested for any fracture caused in transit. A clear ringing sound will be obtained, by tapping lightly on the sides of the wheel with a piece of metal, if the wheel is free from cracks. Resinoid wheels give a dull but solid sound when tapped. The wheels should then be mounted, the balancing weights removed from the collet, and the wheel roughly trued on the face and on the sides if necessary. The wheel and collet assembly is then, after inserting the weights, statically balanced, and when again mounted in the machine the wheel should be finish trued.

Fig. 8.2. Wheel assembly supported on balancing ways

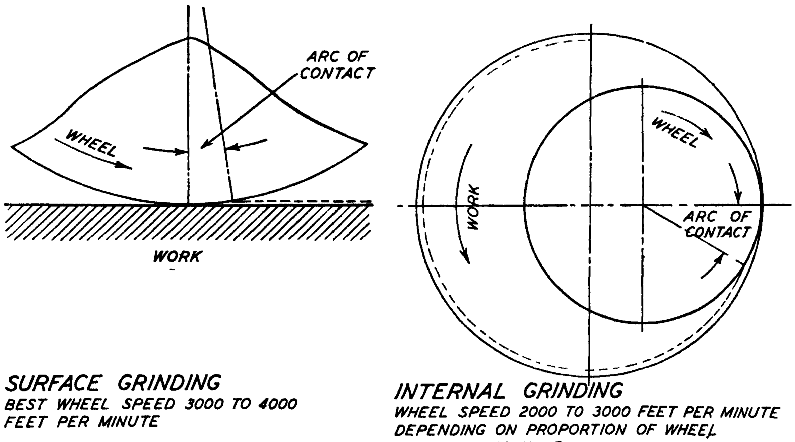
Speeds of Wheel and Work. Fig. 8.3 indicates typical surface speeds of grinding-wheels, which have been found in practice to give the best results on different classes of grinding operations. It will be seen that as the arc of contact between the wheel and the work increases the surface speed of the wheel is reduced. The reason for this will be clear when the conditions under which the chips are cut from the work by the abrasive grain are investigated.

Fig. 8.4 shows the passage of one grit moving across the work. The grinding-wheel A and the work B are rotating clockwise. Almost always in cylindrical and internal-grinding operations the directions of rotations of wheel and work are so arranged that the surfaces in contact move in opposite directions. The depth of cut shown at C is exaggerated. Assuming that the grit is moving past the work at 6000 ft./min. and the work is moving in the opposite direction at



EXTERNAL GRINDING
SMALL DIAMETER WORK WITH LARGE WHEEL. WHEEL SPEED 5000 TO 6000 FEET PER MINUTE

EXTERNAL GRINDING
WHERE WORK MAY BE LARGER THAN WHEEL AS IN ROLL GRINDING. WHEEL SPEED 3500 TO 4500 FEET PER MINUTE



SURFACE GRINDING
BEST WHEEL SPEED 3000 TO 4000 FEET PER MINUTE

INTERNAL GRINDING
WHEEL SPEED 2000 TO 3000 FEET PER MINUTE DEPENDING ON PROPORTION OF WHEEL DIAMETER TO HOLE

Fig. 8.3. Typical surface speeds of grinding-wheels

60 ft./min., it is clear that while the grit entering the work from above is moving from the point D to the position C, where it leaves the work, the work itself will have moved round a distance of 60/6000 or 1/100th the distance DC; the chip DCE will have been removed from the work, the distance CE being approximately 1/100 the length of DC. The diagram purposely distorts the proportions.

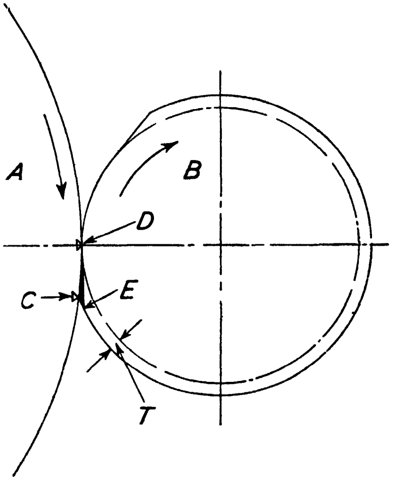


Fig. 8.4. Passage of one grit moving across work

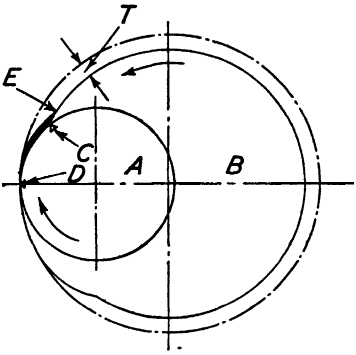


Fig. 8.5. Conditions for internal grinding

The choice of wheel speeds, size of grit, bonding, general grinding conditions, the material being ground, and the work speed, all have the closest possible connection with the form of the chip DCE. If the work speed were reduced to 30 ft./min. the length CE would be halved, and the volume of the chip or metal removed by the single grit would be more than halved. The ideal in all grinding is to give each grit just enough work to do to blunt it sufficiently, so that the increased load on the grit causes the active part of it to split off along a cleavage plane, thus presenting a new cutting facet. The grit may successively split at each pass, finally to be burst from the bonding; the exact sequence of events has apparently never been fully demonstrated.

If work rotating at 60 ft./min. brings about the ideal condition required, then at 30 ft./min. the blunted grit will have a reduced load imposed on it, because of the slower speed, but insufficient to cause it to split or to drag it from the bond. Consequently the grit will not cut freely and the wheel will tend to rub and glaze the work. If, on the other hand, the work speed were doubled the chip DCE would be of much greater volume and would require more work to remove it; the grit would be blunted before it passed through the material, and would be torn from the wheel too quickly. In other words, the wheel would appear to be too soft and would break down too readily.

It will also be seen why the surfaces of the work and wheel are arranged to run in opposite directions. If the work were reversed in direction each grit, instead of entering the work gradually and producing a wedge-shaped chip, would immediately have to contact the full maximum depth of chip CE. This brings a much heavier shock to each grain on contact, and again breaks the wheel down too quickly before the grain has done its effective share of cutting. The action can be compared with *climb* milling.

Fig. 8.5. shows the conditions for *internal* grinding. It will at once be realized that for the same depth of cut the length of arc of contact, and, therefore, the length of chip cut by any grain, is very much longer than in the case of external grinding. Obviously the rate of work done in removing a chip is most important. To remove the same chip in half the time means a great increase in the shock load on any individual grit. In internal grinding, because of the much larger arc of contact in comparison with cylindrical grinding, the chips are much longer; if the grit is to remain sharp during this greater travel through the work, less load must be applied to the grit, which, in turn, means a slower wheel speed.

Midway between external and internal grinding comes surface grinding with a periphery wheel. This may be considered as external grinding of a cylinder of infinite diameter. The arc of contact is midway between that of external and internal grinding and consequently a medium wheel speed is advisable. The work, however, must be traversed to and fro, so that in one direction the condition of opposite directions of movement of work and wheel is fulfilled. In the return stroke of the table, work and wheel are both moving in the same direction, which means that each grit has immediately to enter the work at the full depth of chip, the chip gradually tapering off. This is the exact reverse of the ideal condition, but it cannot be avoided as it is generally impracticable to operate in one direction only.

SUMMARY OF VARYING SPEED CONDITIONS

WORK SPEED

ncrease. 1. Increases the material in the path of each grain.
2. Wheel breaks down more readily.
3. Wheel appears softer.

Decrease. 1. Decreases the material removed per grain.
2. Wheel appears harder.

WHEEL SPEED

Increase. 1. In passing through the work, each grit has a shorter time in which to remove the material, thus throwing a greater shock load on the grit, and tending to break the wheel down and make it appear softer.
2. Owing to the greater speed at which the wheel passes through the work, the work is moved forward less, thus reducing the length and volume of the chip removed and making the wheel appear harder. In general, this second factor predominates.

Decrease. Although less stress is thrown on the grit, with reduced speed the work will travel further during the passing of the grit. This is the predominant factor; the grit will be blunted and broken off from the wheel too soon in its passage through the work, thus the wheel appears to be softer. It is obvious that the speed of the grinding-wheel is of the greatest importance, hence the tendency in many modern grinding machines to drive the wheel spindle by a variable-speed motor which can be set to give the best results. Special precautions, however, must then be taken to avoid running a full-sized wheel at too high a speed.

Arc of Contact. With the smallest arc of contact, as in most cylindrical grinding, a few grits have to carry the entire penetration pressure between the wheel and the work. Increased stress makes any given wheel softer than it would be with a larger arc of contact, so harder wheels are better for small arcs of contact and softer wheels for large arcs. Such considerations are modified if the structure of the wheel gives a closer packing of the grains; more individual grits are then taking the load, and the wheel will appear harder than one with a more open spacing. With the larger arcs, or surfaces, of *contact many more grains are supporting the pressure between wheel* and work, so that a more open structure and coarser grits can be used without concentrating too much pressure on individual grits.

Speed of Traverse. The best speed of traverse is closely connected with work rotational speed. In Fig. 8.6*a*, during each single rotation, the work traverses the distance A—approximately two-thirds the width of the wheel. In Fig. 8.6*b* the distance the work traverses for each complete rotation is one-third the width of the wheel. In the first case the disintegration tends to concentrate at the centre of the wheel; in the second the disintegration is heavier at the sides of the wheel. In general, the condition where the work traverses two-thirds the width of the wheel for each complete rotation is preferable.

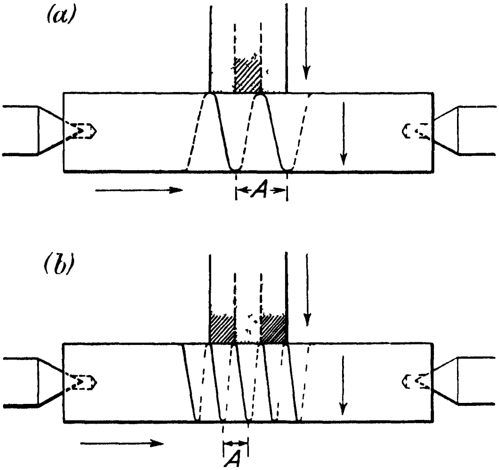


Fig. 8.6. Speeds of traverse

Sixty ft./min. work rotational surface speed gives the best all-round results for *external* grinding, but no hard-and-fast rule can be laid down owing to the very great number of variable factors in every grinding operation. Too low a work speed must be guarded against as it increases local heating with consequent distortion and loss of accuracy.

Conditions are entirely different for *internal* grinding, and a work surface speed of 100–120 ft./min. has proved to be the best normal range.

For *surface* grinding using periphery grinding-wheels the conditions are similar to the grinding of work of large diameter except *that the work traverses in each direction. From 30 to 40 ft./min. is a good normal range, although a slower speed of 20 ft./min. is some*times useful for finishing.

When work is ground by an intermittent or a continuous feeding of the grinding-wheel, without any traverse of the work relatively *across* the face of the wheel, the operation is called *plunge grinding.* The normal width of wheel used for traverse grinding is here also usually appropriate. Wider wheels must be used with caution. If there is a choice between traverse grinding a job 6 in. in length with a 2 in. wide wheel, and grinding the full length with a 6 in. wide wheel, it must be remembered that, in the latter case, to maintain the same conditions of grinding, at least three times the pressure between the work and the wheel is necessary if the wheel is to penetrate the surface of the work satisfactorily. This throws a much greater load not only on the wheel-spindle bearings but on the work itself and the centres. These are more easily distorted, and often no steadying arrangement is effective.

These considerations do not apply so much to centreless grinding, but in all other cylindrical grinding operations, unless a fairly wide tolerance of say 0·002 in. is allowable, it is often better to employ a short traverse of a few inches with a normal width of wheel, than to plunge grind with a wider wheel, particularly when the work is of small diameter.

With many of the latest machines it is possible to obtain a short traverse or oscillation of the table down to ⅛ in., the feed being applied automatically and as regularly as with the normal longer type of traverse. Oscillation of the table is greatly to be preferred to the use of an oscillating wheel spindle. The grinding-wheel spindle is the heart of any grinding machine; it is more difficult to design a grinding-wheel spindle, to give the best results, if the spindle is oscillated in its bearings. The short oscillation of the table is invaluable for plunge grinding as it generally gives a better finish and more consistent sizing than with the true "plunge grind".

Plain or Cylindrical Grinding. Here the work to be ground is usually carried between dead centres; if it is slender relative to its length, adjustable work *steadies* support it against the pressure of the grinding-wheel.

Fig. 8.7 shows a modern machine which will take work up to 20 in. in length (between the dead centres) and 10 in. maximum diameter; the diameter capacity of a plain grinder is nearly always given in terms of swing and not in centre height as with a lathe. This does not always mean that work of the full-swing diameter can be ground with a full-size wheel, as this depends also on the distance the grinding-wheel can be moved back from the centre line of the machine.

In the machine shown, the workhead, tailstock, and steadies are located by an inverted V at the front of the table, and by a flat surface at the rear. The inverted V is especially useful as debris and dirt tend to flow off and away from the grinding surfaces. It will be noticed that the most used parts on the table can be locked in position without the use of spanners, and, as the steadies in particular have to be adjusted in position very readily, quickly operated cam levers are used to advantage. With the work mounted between dead centres a driver-plate is used for rotation. A motor of 1 h.p. drives the work through vee-belts with a two-stage speed reduction; and the belt from the motor is quickly adjusted to the right tension by the adjusting screw A. For quickness of operation the "in" and "out" movement of the tailstock is controlled by a lever, with a catch holding it in the "out" position, thus leaving both hands of the operator free for inserting the work.

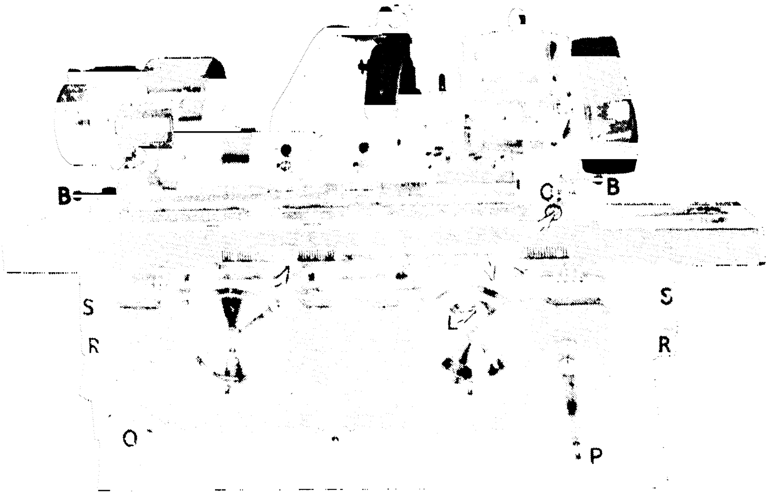


Fig. 8.7. Plain grinding machine
(The Churchill Machine Tool Co. Ltd.)

The sliding tailstock barrel is an important part of the machine. In quantity production the tailstock is operated many hundreds of times in a day; the slightest shake of the barrel in the body of the tailstock makes accurate grinding impossible.

The upper part of the table is arranged to swivel relative to the lower part on a central pivot and its ends can be locked by the clamps B. This enables taper work to be ground, the degree of taper being shown by a scale at C; a screw adjustment at D makes for easy setting. The upper portion of the table is supported on four cross-faces; in the latest methods of building a grinding machine of this type, these strips are ground on a *Slideway grinding machine* (see Fig. 8.15). The plane of the surface of the strips must be parallel to a plane passing through the work and the grinding-wheel spindle axes, otherwise it is impossible to grind taper work accurately.

The lower portion of the table of the machine is carried in vee and flat ways in the main body. In modern plain grinding machines, except the larger and heavier types, tables are traversed hydraulically. In Fig. 8.7 the piston rod of the hydraulic cylinder is connected directly to the table, but in such a way that the accurate movement of the table in its ways is not in any way restricted. Adjustable dogs E, with fine screw adjustment, limit the traverse. The traverse can be by hand with wheel F, which operates through an internally cut gear, giving a reduction and consequently a sensitive movement of the table. A small lever G provides a finger-tip control for disengaging the hand traverse of the table and engaging the hydraulic movement, or vice versa. The lever H adjusts the speed of the table traverse; traverses down to $\frac{1}{8}$ in. can be used.

The reverse lever J is operated by the reversing dogs, and is also used for hand control of the table. K is the hand feed for the wheelhead and L is a fine adjustment giving an advance to the wheelhead of 0·0001 in. for each step of movement, i.e. a removal of 0·0002 in. on work diameter. This fine adjustment also carries round with it the dead stop and the cam for disengaging the automatic ratchet feed. When feeding by hand, only the dead stop comes in contact with latch stop, M. The automatic feed operates at each end of the traverse.

The grinding-wheel is of 20 in. diameter and is normally 2 in. wide. The wheel spindle is of nitralloy steel, which possesses excellent wearing qualities and is hardened without having to bring it to its critical temperature, making it free from thermal distortion in operation and capable of running safely with a very thin oil film. It is a great advantage if filtered oil is supplied to the bearing before rotation is started.

The motor driving the wheelhead is of 10 h.p. and drives the grinding-wheel spindle through multi-vee ropes. A 2–3 h.p. motor drives the hydraulic pump for the table traverse; and a $\frac{1}{4}$ h.p. motor, which forms a self-contained unit with the coolant pump, supplies coolant to the grinding-wheel and the work, after the used coolant has been cleared of grinding debris in a swarf separator.

At N, push-button control for all motors is brought to a convenient operating point, O is the variable work-speed control, and the handle P gives a quick hand traverse to the wheelhead. The projections R at each end of the bed—there are others at the rear of the machine—are for slinging. Oil is continually pumped up to the slides, and eventually flows into collecting chambers S, whence it passes through a filter back to the sump. All vital and continuously running parts on the machine, such as the wheel spindle and table traverse, are automatically and continuously supplied with oil. All other moving parts are lubricated by an oil-gun through conveniently placed oiling nipples.

There are similar plain grinders arranged, in addition, with an automatic cycle making them suitable for mass production as well as for small quantities. They may have levers for starting the hydraulically operated wheelhead forwards or back, and for controlling the rate of the hydraulic in-feed during grinding; a control disc for setting the period of "dwell" at the finish sizing point from zero to a few seconds or longer. An indicating lamp remains alight during this period. A sector dial at the back of the wheelhead with a pointer indicates how the wheelhead is moving because, during in-feeding, the rate of movement cannot be seen without magnification. In most modern grinding machines provision is made for regrinding the dead centres to the correct angle, but it is equally important that the centres in the work itself are also as accurate in their true cone shape. This point is given insufficient attention in most shops. Very accurate work requires that all work centres be ground, special grinding machines being made for this operation.

In modern production practice there are many plain grinding operations which cannot be carried out on dead centres or on a mandrel between dead centres; the work must either be chucked on a live work spindle, or, even if the work can be carried on the centre at the tailstock end, it must be chucked at the workhead end. In such cases, however, it must always be remembered that accuracy is not so easily obtainable as with work ground on dead centres. A live workhead is bound to have its own slight inaccuracies of rotation, and if there is much overhang of the work when chucked these may be magnified many times at the surface to be ground. The greatest importance must, therefore, be attached to the bearings of a live spindle workhead; many of the difficulties can be overcome by sufficient spacing of the bearings.

A good example of a live spindle workhead is shown in Fig. 8.8, the span of whose bearings is nearly 3 ft. Here the bearings are of the plain type; there are several other points of interest in this machine, which is for grinding taper and parallel types of roller-bearing races. The wheelhead is arranged to swivel, and the grinding-wheel can be mounted on either end of the spindle. The workhead also is arranged to swivel to different angles according to the angle of the taper in the races and is mounted on a cross-slide to bring the work, after it has been swivelled, once more over the centre line of the machine. The work spindle carries a circular magnetic chuck.

Fig. 8.8. Live spindle workhead
(*The Churchill Machine Tool Co. Ltd.*)

Heavy Plain Grinding Machines. Hydraulically operated machines of the type described are usually built up to capacities of 18 in. swing; above this size plain grinding machines are often fitted with gear traverse. The conditions for operating these machines are quite different. The work is much heavier, the operations take a much longer time, and the operator is not called upon continually to use the controls, as he is with the smaller machines.

A gear traverse through a suitable gear box gives a constant speed even at a very slow rate, say for truing the grinding-wheel with a diamond, when the load on the table is negligible. Hydraulic systems work best at slow traverses when operating against a heavy load, as in a heavy miller.

A uniform speed of traverse is essential; this is particularly noticeable when finishing large diameter work in a heavy plain grinding machine. Even very small variations in speed of traverse are immediately shown up in the finish of the work, because the grinding-wheel is cutting under variable conditions. If, for instance the speed of traverse drops suddenly when finishing a heavy roll, work costing several hundreds of pounds may be ruined. For these and other reasons modern practice tends to retain gear traverse for the heavier plain grinding machines.

In Fig. 8.9 the type of *work steady* used for plain grinding is shown. The steady pads, which are usually of hard wood, bear on the work at two positions approximately 105° apart. The angular spacing of these pads is important; were they spaced at 90°, or at any other regular fraction of the 360° round the work, it would be difficult to grind cylindrically with accuracy, because of "lobing" (in which the work gauges accurately by micrometer at all diameters but will not enter the corresponding ring-gauge).

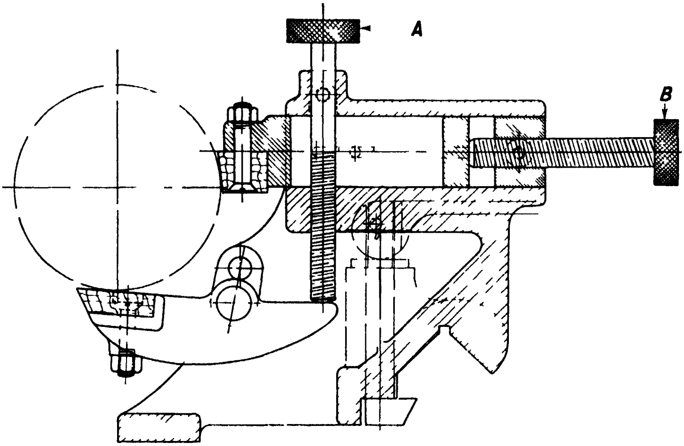


Fig. 8.9. Work steady

The lower shoe of the steady is adjusted by the hand-screw A and the horizontal shoe by the screw B. The lower shoe is pivoted on a pin that can be inserted in another hole shown immediately above the steady-pivot, which is used when smaller diameters are being ground. Exactly the same type of steady is used on small and large plain grinding machines.

There is still misconception about the use of work steadies. Their principal use is to support the work so that it will not be deflected either by its own weight or by the pressure of the grinding-wheel. Obviously the more slender the work relative to its length the more steadies must be used, and they must also be more closely spaced. The misconception arises when testing a machine. A general test is to see whether the machine is capable of grinding a sample bar parallel and accurately cylindrical from end to end. It is sometimes stipulated that the test grind must be carried out without steadies. In the case of a bar 3 ft. long and 4 in. in diameter such a test is satisfactory, but if the bar were only 2 in. in diameter pressure of the grinding-wheel at the centre of the bar would cause sufficient deflection to show on a clock indicator, and such a test without steadies is no test at all. *Any such test bar should have a diameter of not less than one-tenth of its length, if the test is made without steadies.*

An even better test is to grind a short stiff bar at the extreme right-hand end of the table; then to move the workhead and tailstock so that the bar is reground at the centre sections of the table; and finally to grind it with the workhead and tailstock at the extreme left end. The machine should grind strictly parallel at all three positions, the test being a comprehensive check of the machine.

The correct use of steadies on long slender work calls for the highest skill; for example, the grinding of a bar 6 ft. long and 1 in. in diameter presents almost insuperable difficulties if a high degree of accuracy in parallelism is required. Here the machine is not responsible for any want of parallelism, the hand operation of the steadies being the principal factors

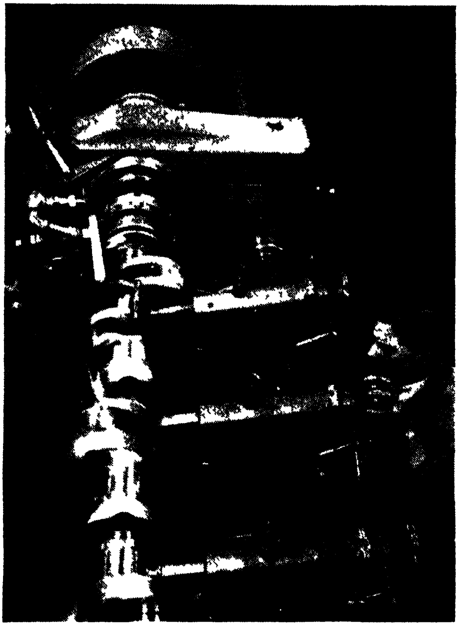


Fig. 8.10. The use of steadies

(*The Churchill Machine Tool Co. Ltd.*)

The use of steadies when grinding the journals of a heavy eight-throw crankshaft is shown in Fig. 8.10. Such a crankshaft is even more flexible than a straight bar of similar diameter and the correct adjustment of the steadies is absolutely essential. Crank-pins of all but the heaviest crankshafts can be ground by the use of throw blocks, which offset the pins and bring them into the centre line of the machine.

Plain Grinding with Formed Grinding-wheel. Many special plain-grinding operations are carried out with the face of the grinding-wheel formed to the profile desired (Fig. 8.11). A power-driven wheel-forming device may be advantageously mounted on the wheelhead of a plain grinding machine, In contact with a former bar of the profile desired is a spring-loaded vee follower, on a compound power-operated traverse slide. On the opposite side of this slide is a diamond, in contact with the periphery of the grinding-wheel and thus imparting to it the desired form. Mounting such a device on the wheelhead avoids the necessity of removing it from the table and allows of forming the wheel without removing work from the machine. Similar devices may be mounted on the table, preferably at the end, so that re-forming requires only that the table be traversed to a new position, leaving the work and forming device in situ.

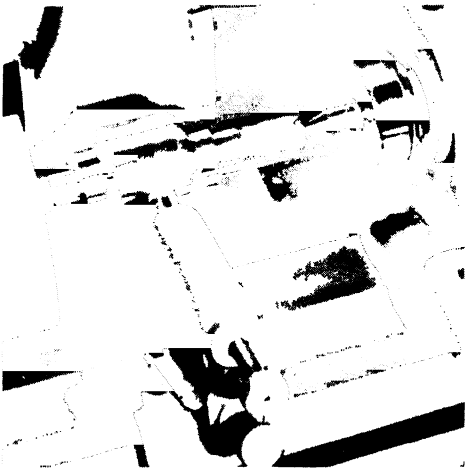


Fig. 8.11. Grinding with formed wheel
(*The Churchill Machine Tool Co. Ltd.*)

Whenever the wheel is to be retrued it is necessary only to move the table to the extreme left of the machine to bring the diamond into use. This is better than having to lift and mount a truing device in position between the workhead and tailstock every time it is required to true the wheel.

Plain grinding is thus by no means confined to cylindrical work; reference should also be made to the grinding of cams and camshafts, and to the grinding of parts where a projection prevents the work being rotated continuously. For these latter, an oscillating motion is applied to the work either by linkage or by a reversing motor, so that the grinding-wheel forms a cylindrical surface but does not come in contact with the projection.

The use of twin wheels of different diameters, so that two diameters can be ground simultaneously on the same piece, has often proved very useful in production. The wheels should be trued with a single diamond controlled by a former bar. If two diamonds are used, different rates of wear on them may cause errors in the work. In quantity production where several diameters have to be ground on the same shaft the best practice is to grind right through the batch again for the second diameter, and so on until all the diameters have been ground.

Roll Grinding Machines. The roll turner was a man of exceptional skill, acquired by long experience, but the accuracy he attained does not meet today's requirements for paper making, sheet metal work, rolling of both hard and soft metals, strip rolling, flour milling, rubber processing, rolling metal foils, the processing of food products, or for the making of cellophane and other synthetic tissues. A very high degree of accuracy is required; often it is necessary for the roll to be finished with a convex and sometimes a concave camber.

For the precision grinding of large paper-mill rolls the usual practice is to mount the roll between centres and grind the journals, which are then carried in special bearings, the roll body being ground while the roll is rotating on its own bearings. Supporting steadies are also used. The same type of machine is used for grinding the heaviest rolls used in steel-rolling mills.

It must never be forgotten that the grinding-wheel is a multitude of cutting tools, each producing its machine mark. Even with the ordinary commercial finish clearly showing the grinding marks the work can be of a high degree of accuracy; any attempt at finishing with a hard wheel at this stage, or the use of a polishing operation, may give a burnished finish, but it will destroy the accuracy already produced by the true grinding operation. To obtain a high degree of finish by grinding it is necessary gradually to reduce the dimensions of the cutting marks, and the final traverse should do no more than remove the crests of the now infinitely small marks, without penetrating below the solid diameter of the work. In this way finish is built up without destroying accuracy. With a well-designed, well-kept, precision grinding machine, it is not difficult to obtain the highest degree of accuracy, but it is fatally easy to lose it by ill-considered attempts to obtain finish.

Internal Grinding. The outstanding points of difference from other grinding operations are the relatively small diameter of grinding-wheel which must be used, and the large area of contact between the grinding-wheel and the work, which is, as it were, wrapped round the wheel, and reduces the metal-removal capacity to such an extent that internal grinding presents special problems to the production shop.

Fig. 8.12 shows a plain internal grinding machine, the word "plain" signifying that grinding is controlled by hand and there is no automatic cycle. This type can probably deal with two-thirds of all internal grinding operations, especially for small batches. Normally its capacity is for work up to 12 in. outside diameter; the usual range of bores ground is from ½ in. up to 4 in. in length. Both smaller and greater diameters and longer lengths can be dealt with, but difficulties increase considerably if the length of bore exceeds five or six times the diameter.

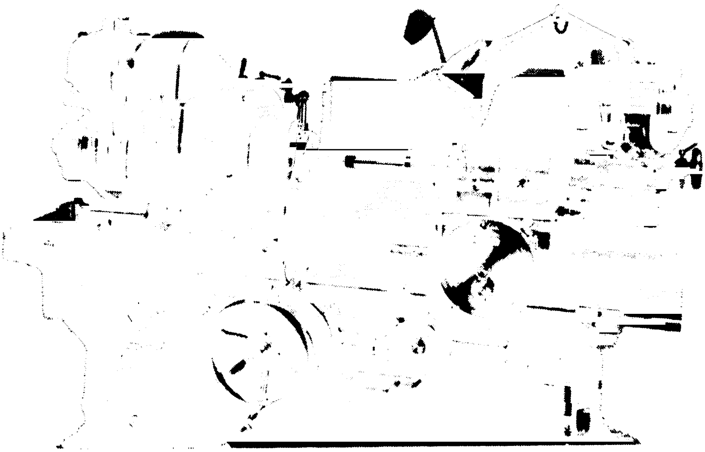


Fig. 8.12. Plain internal grinding machine
(The Churchill Machine Tool Co. Ltd.)

Grinding is expected to give precision and generally final results; this means a maximum of rigidity in every element of the grinding machine. The weakest element is the internal grinding spindle which must project into the hole to be ground. A long narrow bore means a long slender spindle which no cleverness in design can make rigid. The latter stages in such a grinding operation must be carried out with caution verging on timidity, because the pressure between the grinding-wheel and the work surface inevitably deflects such a slender spindle. Nevertheless, it is possible under advantageous conditions to grind bores with a length ten or even twelve times their diameter.

In Fig. 8.12, the work to be ground is carried on a live spindle workhead which, in turn, is carried on a long table which traverses to and fro. The grinding-wheel spindle is mounted on a cross-slide, which applies feed to the grinding-wheel. The feed-slide can be operated by hand, or automatically, at each end of the traverse of the work.

Smaller types of internal grinding machines for instrument work are also made, but, as the limiting factor in all internal grinding is the relation between diameter and length of the grinding spindle, it follows that the grinding of small bores below $\frac{1}{4}$ in. in diameter presents new difficulties. The size of the machine may be reduced to such an extent that its mere bulk and weight are an insufficient basis for an all-round rigidity. It is advisable not to plan for grinding bores of extreme lengths relative to diameter if a change in design of the component, or another sequence of operations, can avoid the resulting awkward internal-grinding operation.

In another type of internal-grinding machine a planetary motion is given to the grinding-wheel spindle; such machines are usually called cylinder grinders. They are used where the work cannot be rotated on the live spindle of a workhead, and are invaluable for grinding two or more bores in line—in such work as gear-box casings, crank casings, and machine tool workheads. The best method of internal grinding is, however, to rotate the work, as in this way many possible errors are avoided; the planetary method of grinding should be used only where the work, owing to its size, weight, or shape, cannot be conveniently carried on the live spindle of a workhead. The range of a planetary grinding machine can be increased by mounting a live spindle workhead on the table, in which case the planetary motion is cut out. Cylinder grinding machines cover a wide range, from bores down to 1 in. diameter (or even less) to large bores over 10 ft. in length.

AUTOMATIC INTERNAL GRINDING MACHINES. Machines which automatically size the work have entirely changed the general practice of internal grinding in the last thirty years and have, despite inherent difficulties, brought the operation, from the production point of view, more into line with other grinding operations. In this type of machine the operator inserts the work, and starts the cycle; the rough grinding operation proceeds, the work being then automatically and quickly withdrawn to the run-out position. The grinding-wheel is then trued by the diamond which comes into its position automatically, and the operator then moves a lever to continue the cycle, during which the work is finish ground. Sizing is controlled by the position of the diamond when it is in its truing position. The diamond can be set with extreme accuracy by a micrometer adjustment. Feed to the grinding spindle is through a two-stage cam for the roughing and finishing operations of the cycle respectively. This machine is capable of an output many times greater than is possible with a hand-operated machine.

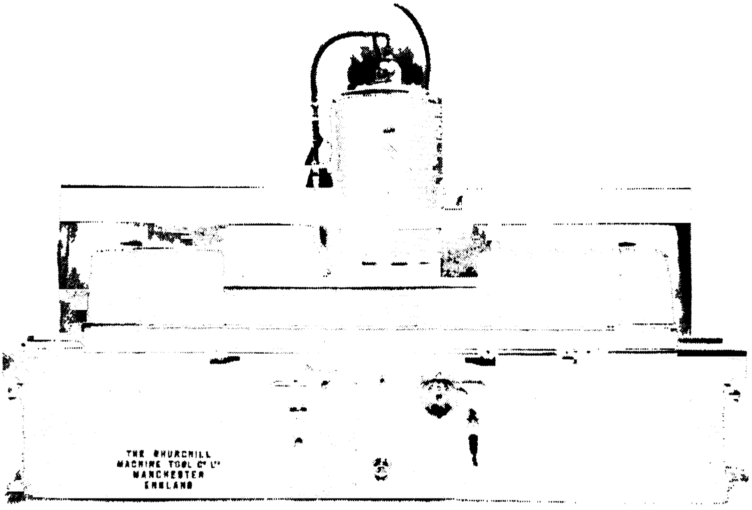


Fig. 8.13. Surface grinding machine

(*The Churchill Machine Tool Co. Ltd.*)

With these automatic internal grinders it is usually possible to grind an internal face or shoulder at the bottom of a blind bore, and also external faces at the same setting as for the automatic sizing of the bore. This is accomplished by mounting the internal spindle or spindles in very accurately made square sliding housings. An even faster automatic machine is one in which the grinding operation is of the plunge type, enabling blind holes to be formed right to the bottom with safety.

Surface Grinding. The grinding of flat surfaces can be carried out in several ways. For direct grinding from rough castings the vertical spindle type of machine with abrasive segments is generally used; with a high-power electric motor built directly on to the grinding-wheel spindle, and with hydraulic traverse to the table giving traverse speeds up to 100 ft./min. or more, it is one of the most productive machines in the whole range of grinding. As the resulting accuracy is greater than is possible with planing or milling, the value of this type of machine will be realized, particularly as roughing and finishing operations are condensed into one.

Fig. 8.13 shows a machine of this type with a 35 h.p. self-contained motor driving abrasive segments making up a ring 18 in. diameter.

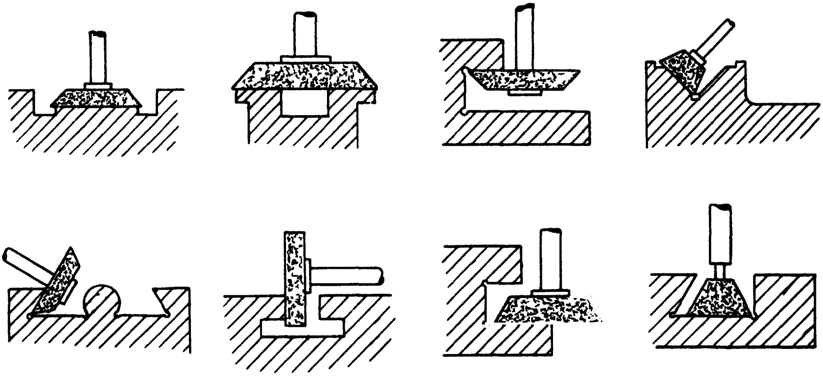


Fig. 8.14. Some operations in grinding the dovetail of a precision machine tool slide

All surface grinding machines should be designed so that the surface of the table can be ground by the wheel or segments of the machine. Not only does this allow the table to be trued up at any time, but it ensures that all work placed on the machine will be ground parallel with the table; this is an advantage which cannot be exaggerated. The grinding-wheel spindle should, for nearly all operations, be tilted so that one edge of the wheel clears the work by a few thousandths of an inch. Unless the work is nearly as wide as the wheel the hollowing effect of tilting the wheel in this way is negligible, but the metal removal capacity of the machine is greatly increased. Most machines today are fitted so that the tilt of the wheelhead can be adjusted; in an exceptional case where a wide surface must be finished to extreme flatness the head can be brought into the strictly upright position, and very light finishing cuts applied. An attempt to use the machine with strictly vertical spindle in ordinary work results only in a waste of horsepower and grinding segments.

A similar type of machine is also made with cross-traverse to the wheelhead, the machine being then of the *plano* type.

Another range of surface grinders uses the periphery of the grinding-wheel, which is carried on a horizontal spindle. Greater accuracy is obtainable with this type of machine, but, as usual, at the expense of rate of metal removal and output. The horizontal spindle type of surface grinder is, therefore, invaluable in the tool-room, and in the grinding of relatively small parts. The work can generally be carried conveniently on a magnetic chuck.

SLIDEWAY GRINDING MACHINES. The greatest accuracy in surface grinding is obtained by the use of a saucer-type wheel, because only the thin rim of the wheel is presented to the surface to be ground, and very light cuts are taken. It is more of a generating operation than is the grinding with the periphery wheel, which obviously cannot grind a surface to a greater accuracy than that to which the wheel face has been trued. The greatest use of the saucer-type wheel for surface grinding is made in the slideway grinding machine which is used so extensively today in machine-tool manufacture.

Fig. 8.15. Slideway grinding machine: use of the "saucer" wheel

The manner in which the saucer wheel is applied is shown in Figs. 8.14 and 8.15 in grinding the dovetail of a precision machine-tool slide. The angle at which the motor-driven grinding spindle is set is accurately obtained by setsquare and sensitive level. All six surfaces of the casting are ground on this machine; this operation follows the grinding of the vee and flat ways on the underside of the casting. In Fig. 8.15 the casting is shown mounted on a master plate contacting the previously ground vee and flat surfaces. The surface left by slideway grinding is not of the mirror type, as such a finish would prevent proper lubrication.

Centreless Grinding. This is now employed for grinding many classes of work that used to be ground between dead centres on a plain grinding machine, and also for many that previously presented great difficulty in grinding at all. The principle of the centreless grinding machine is shown in Fig. 8.16.

The scope of centreless grinding is, however, very much wider than is implied by its name. A great deal of plain grinding that previously had to be chucked on a live spindle workhead can be ground on the centreless machine at incomparably higher rates of production; and also a great deal of form, multi-diameter, and shoulder work. One of the principal reasons for the high output of the centreless machine is the much better support that can be given to the work during grinding than with the plain grinder. In a normal plain grinding machine the pressure of the grinding-wheel is resisted by the centres, and generally by steadies at one or more positions; with slender work the efficiency of the grinding is largely due to the skill of the operator in manipulating the steadies. In centreless grinding, however, the work is often supported over its full length from three directions; from the face of the grinding-wheel, the face of the control wheel, and the face of the angular top workblade. With such complete support, grinding can be carried out to the limit of capacity of the grinding-wheel to remove metal. Rigidity of the whole machine is, therefore, of even greater importance than with other grinding machines, in which either the work or an internal grinding spindle limits the grinding load that can be applied. There can be no such thing as a satisfactory centreless grinder of light construction even for light work.

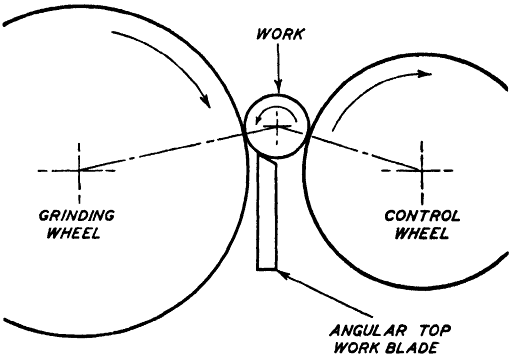


Fig. 8.16. Centreless grinding

The grinding-wheel rotates in the same direction as on a plain grinder, but the work is rotated in the opposite direction. The control wheel rotates the work, the angular top workblade serving to maintain close and firm contact between the work and the control wheel. The control wheel does no grinding although it is in the form of a very fine grit wheel; tilting the axis of the control wheel causes any point on the work to rotate in a spiral path, and, in this way, the work automatically traverses through the gap between the wheels.

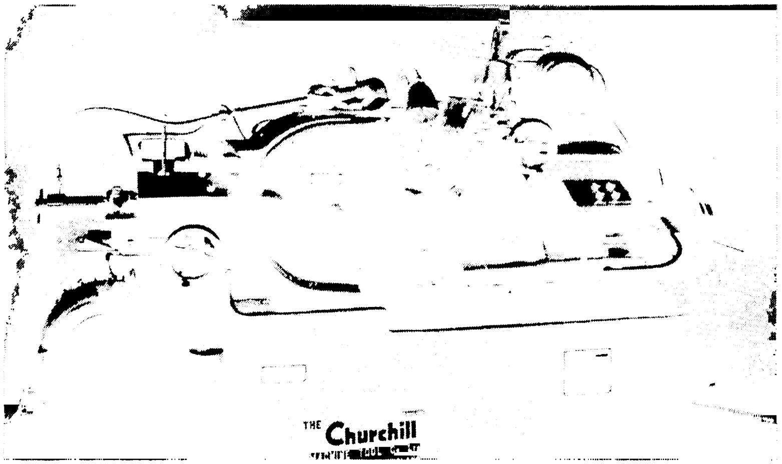


Fig. 8.17. Centreless grinder

(*The Churchill Machine Tool Co. Ltd.*)

This principle is used in all *through-feed* grinding, whether of short or long pieces of bar or tube work; the control wheel and the work-blade, on their slides, are set at a definite distance from the grinding-wheel and during the passage of the work no further feed is applied. The control wheel is also tilted for shoulder, multi-diameter, or form work, but with the object of keeping the work firmly in contact with an endstop. In this class of *in-feed* operation the hand-operating lever is raised to open the gap between the wheels, and the work-piece is placed on the workblade between the wheels. The downward movement of the hand lever causes the control wheel and workblade to move forward, thus applying feed during grinding up to a dead stop with a micrometer adjustment to 0·0001 in.

Ground bar stock is now, thanks to centreless grinding, a common commercial product. The operation is a straightforward through-feed one, except that it is essential to provide long guides to support and carry the bar in the correct position as it enters and leaves the wheels.

In setting up the centreless grinding machine, a most important point is the height of the work-centre in relation to the centres of the grinding-wheel and control wheel, this height being controlled by the vertical setting of the workblade. In the latest types of work-rest for through-feed and in-feed work the correct setting for all diameters is obtained automatically, so that changing from one diameter of work to another occupies little time; the centreless machines can thus be used to great advantage even for limited runs.

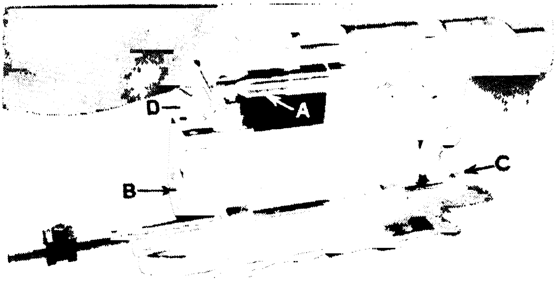


Fig. 8.18. Concentric fixture

Concentric grinding presents a perpetual production problem—the grinding of bores strictly concentric with the outside diameter. One method is to grind first the outside diameter of bushes or similar work on a centreless machine, and then the bore on an internal machine with the bush held in a plate-collet or other type of chuck gripping with the highest possible concentric accuracy. But this is difficult with some classes of work, and here the concentric method becomes invaluable.

Bores are ground first on an internal grinding machine, and then the outside on a centreless machine. Fig. 8.18 shows a concentric grinding fixture, which is located between the wheels. The work is slipped on to the arbor A which is free to float horizontally about the fulcrum B, to and from the grinding-wheel surface and for which D is the outboard support. Spring pressure tends to hold the work towards, but not in contact with, the control wheel. As the control wheel is fed towards the grinding-wheel it thrusts the work into contact with the latter until it has been ground to a size determined by a previously-set dead stop. The withdrawal of the control wheel automatically ejects the work from the arbor through the spring-loaded ejector mechanism C coupled to the infeed operating lever. Concentricity is easily kept within very fine limits.

The *advantages of centreless grinding* include:

1. In through-feed grinding of short pieces in turn the operation is continuous and idle time is negligible.
2. Heavier cuts can be taken, even when finishing pieces, because with properly designed work-rests deflection cannot take place, as the work is usually supported through its entire length.
3. No axial thrust is imposed on the work during grinding. Slender parts are easily distorted by the spring in a tailstock, or by a badly adjusted steady on a plain grinding machine.
4. Errors due to work-centres are eliminated and considerably less material can be left for the grinding operations, both roughing and finishing.
5. Any slight variations between piece and piece due to wheel wear are half those obtained by grinding between centres.
6. It is possible to mount the grinding-wheel spindle directly in the main casting of the machine; the advantage of the rigidity thus obtained cannot be exaggerated.
7. Unskilled labour can be used for nearly every operation; with automatic hoppers one operator can attend to several machines.

The foregoing notes refer to external grinding but there are a few cases where centreless internal grinding is carried out successfully. Cylinder liners are produced by a combination of centreless and internal grinding, the liner being ground internally while it is rotated in a manner similar to that used in ordinary centreless grinding. This method ensures concentricity, and is particularly useful when dealing with thin-walled products. As in all other internal grinding operations, the diameter of the bore must be large enough to admit a rigid spindle.

Spline Grinding. Splines or serrations (Fig. 8.19) today have to be produced with great accuracy, involving from 2 to 50 or more splines. The work is traversed under a formed grinding-wheel, and indexed automatically on a new spline at each traverse.

The special point of interest is the method of truing the grinding-wheel to the required form: two slides set at the required angle true the flanks of the wheel which have to grind the flanks of the spline; a third diamond is moved about a centre corresponding with the centre of the work, and trues the grinding-wheel to grind the root diameter of the splineshaft. All three diamonds are moved simultaneously by the movement of one lever, advantage being taken of the diamond position to give automatic sizing in a similar manner to that used on an automatic sizing internal grinding machine. Accurate indexing on the automatic workhead is naturally of the greatest importance; it is possible to grind splines with standard equipment to within 0·0001 in. circumferential error.

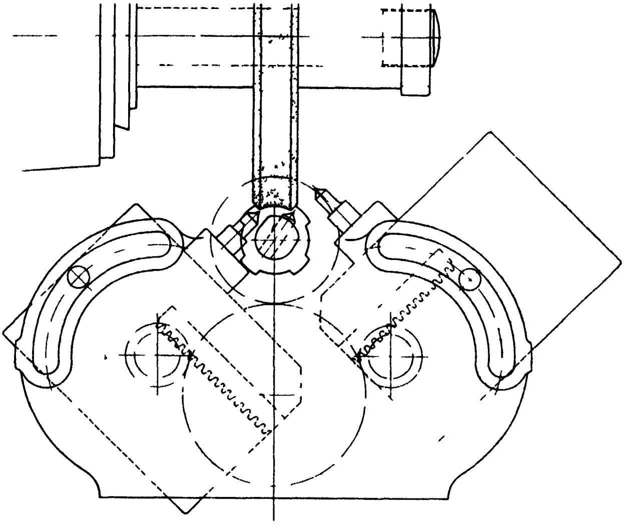


Fig. 8.19. Spline grinding

Universal Grinding Machines. These combine many of the features of several of the machines already described. In general, a universal grinding machine is a plain or cylindrical grinder with the following additions: (1) Swivel workhead. (2) Live work spindle that can be locked for dead centre grinding. (3) Swivel wheelhead. (4) Internal grinding spindle for use with work chucked on the live spindle workhead. Such a machine is shown in Fig. 8.20.

It will be appreciated that the standard type of universal grinding machine is not only invaluable in the tool-room but also has its uses for some special operations in the manufacturing shop. In common with most plain grinders the table of the universal machine can be swivelled for grinding tapers.

On many of the latest types of machine an internal grinding spindle can be brought into use without disturbing the main grinding-wheel. Universal grinders, for convenience in a wide range of work, are invariably fitted with a flat table top, and in this they follow the established practice with internal grinding machines.

Universal grinding machines are made in all sizes, from the very smallest for instrument work up to those of 24 in. swing and

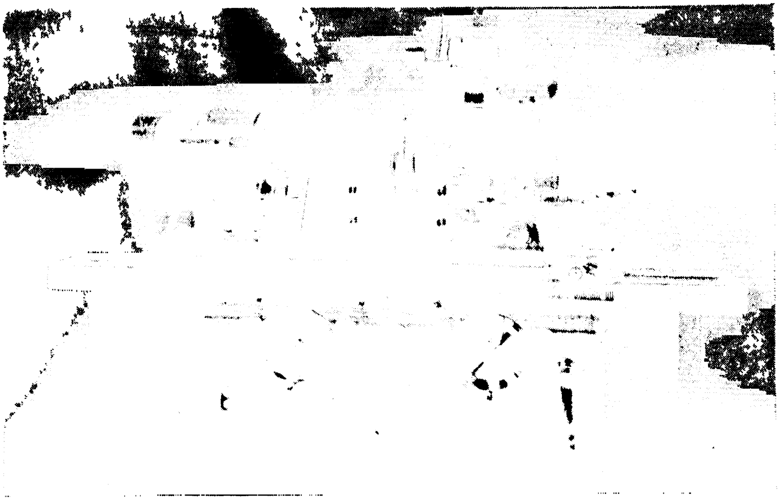


Fig. 8.20. Universal grinding machine

(*The Churchill Machine Tool Co Ltd*)

10 ft. or more in length; a universal grinder of special type for large roller-bearing races will accommodate bearing rings up to 72 in. in diameter.

Alignments. The precision grinding machine generally carries out final operations after other machine tools have removed the bulk of the metal; the alignments to which precision grinding machines must be built and maintained are, therefore, of greater importance than in other machine tools. In relatively short machines of not more than seven tons, the best practice is to carry the machine on three feet; the position of the feet is chosen when the machine is designed, so that the weight of the machine is borne without any distortion of the sliding ways, or of the relative positions of the vital parts of the machine. In a cylindrical grinder the paramount questions are whether the machine will grind work round and parallel to within the closest tolerance (often 0·0001 in.) needed today; whether it will continue to do so when it has warmed up after being in use several hours; and also whether it will maintain its alignments over a long period of use. Very few experiments need be carried out to test the practical value of a grinding machine. A long series of alignment tests, such as have been suggested in some quarters, may lead to misleading results, as many of such tests have no bearing on the production of accurate work.

Machine Checking. A plain grinding machine should grind a short test bar, between dead centres at three widely spaced positions along the table, accurately round and parallel at each position; the best practice is for the diameter of the test bar to be at least one-fifth of its length so as to avoid a misleading result by the use of steadies. If the wheelhead accurately repeats feed, the tailstock barrel is close fitting at all positions, the tapers of the centres accurately fit their bores, and a true taper can be ground with the table set over, then it can be accepted that the machine will produce satisfactory work.

With surface grinding machines the first requirement is that the table of the machine can be ground by the machine's own wheel. The down-feed should repeat accurately on a clock, and with a horizontal spindle machine or plano grinder the cross-feed should also give accurate repetition. The rise and fall of the wheelhead should be strictly parallel with itself at all positions.

With internal grinding machines the equality of heights of the work spindle and internal grinding spindle, and the constancy of these relative heights when the table is swivelled for taper grinding, are points for inspection, although the former is of no consequence if parallel work only has to be ground. It is possible for this type of machine, in particular, to pass a whole series of arbitrarily selected alignment tests, though the design of some part of the machine may prevent its ever being of any value for accurate internal grinding.

It will be seen therefore that there is a large number of other conditions, besides alignment, which contribute to the success of a precision grinding machine. The best test is based on the work produced.

Spindle Bearings. The most important part of any grinding machine is the bearing on which the grinding-wheel is carried. With the high-speed bearings required for internal grinding spindles, high quality ball bearings are still essential in general practice. With this one exception, however, grinding experience, over fifty years, has resulted in the adoption of a spindle running in solid bearings; it has proved to be the best type for consistency, finish, and accuracy, under all conditions.

In the earlier precision grinding machines cap-type bearings proved entirely satisfactory, though it was necessary to leave considerable running clearance between the spindle and the bearing, the former floating, to some extent, on the relatively thick oil film. Nitralloy steel spindles, hardened below the critical temperature, and so free from internal stress, which maintain an absolutely straight axis under all conditions, are now available; they allow smaller clearances to be employed with safety. A grinding-wheel spindle that could float even by 0·001 in. in its surrounding oil film could not give consistent results when tolerances of one-tenth of this figure were required in the part to be ground.

Grinding Times. Unlike operations on other machine tools, it is not possible to calculate grinding times on a basis of speed and feed, the number of variable factors being too great. Doubling the amount of material left on for grinding more than doubles the grinding time; the work heats up more and a distortion with an increase of temperature, which would be negligible on any other operation, tends to make an accurate finish on the grinding machine impossible. The other main considerations are the accuracy and finish required; with every step up in both these directions, grinding time is lengthened at an increasing rate.

With soft and unhardened materials, large diameters can be left with 0·02 in. to 0·04 in. for removal on the grinding machine, but on smaller work, and hardened work particularly, the amount of material left on should be as small as possible; 0·01 in. to 0·015 in. is generally good practice. For the internal grinding of hardened work it is advisable not to leave on more than 0·008 in. to 0·01 in. diameter.

A fairly reliable basis for calculation of grinding times is the capacity of the particular grinding machine and grinding-wheel for removing metal. Such a basis of calculation gives satisfactory results for cylindrical grinding on a plain grinder. The results are more uncertain with internal grinding which has more variable factors than external grinding. For surface grinding the capacity for metal removal still forms a good basis for calculation, but full account must be taken of the area to be ground during any finish grinding operation. The amount of metal removed in the earlier stages is relatively large compared with that removed towards the end of the operation.

There are so many factors affecting metal removal that no general guide can be given which would not be misleading. These include grit size of grinding-wheel and suitability of bond, stability of wheel spindle and bearings, strength of wheelhead and wheel drive and rigidity of work support. On plunge work, if all the preceding factors are favourable, wheel width is a major factor.

ULTRASONIC MACHINING

By E. A. NEPPIRAS
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Principles. The breaking and cutting of brittle materials by repeated and highly concentrated blows has for long been performed by pneumatic hammers, etc. This principle has now been applied to tools for workshop use for carrying out a wide range of machining operations in brittle substances.

The obvious advantage of a reciprocating tool compared with rotary devices is that the unidirectional motion ensures that the cavity produced in the workpiece will follow the shape of the tool, provided the particles of material removed are small compared with the tool dimensions. In practice, this is done by restricting the motion of the tool so that the chipping occurs on a microscopic scale. To compensate for the small vibration amplitude the frequency is increased to the order of 20,000 oscillations per second. This is above the upper limit of audibility, and the process is thus silent.

The high-frequency vibration is produced by means of a resonant electromechanical transducer, preferably of the magnetostriction type. Magnetostriction is the small change in dimensions obtained when ferromagnetic materials are magnetized. A transducer core of ferrite material or laminated metal may be driven into mechanical resonance by passing a current at the correct frequency through a coil wound round it, the transducer being biased magnetically by applying a suitable d.c. polarizing field (See Fig. 8.21). The resonant movement of the operating face of the transducer, which is arranged to work vertically, is only of the order of 0·0005 in., but this can be amplified by attaching to it a suitable resonant tapered horn of brass or other metal. A system of standing waves is set up in the horn, the energy supplied at the larger and more massive end being transmitted to the smaller in such a way that the amplitude of vibration is increased in proportion to the reduction in diameter. In this way, longitudinal vibrations with amplitudes of the order 0·001–0·003 in.

are produced. These are suitable for such operations as piercing, blanking and grinding. For operations involving sidewear of the workpiece—tapping threads and lapping or polishing drilled holes—a flexing type of vibration is preferable. This is conveniently obtained by fixing to the horn an additional metal stub of suitable length, with its axis perpendicular to the direction of the drive vibration, to which the tool is attached.

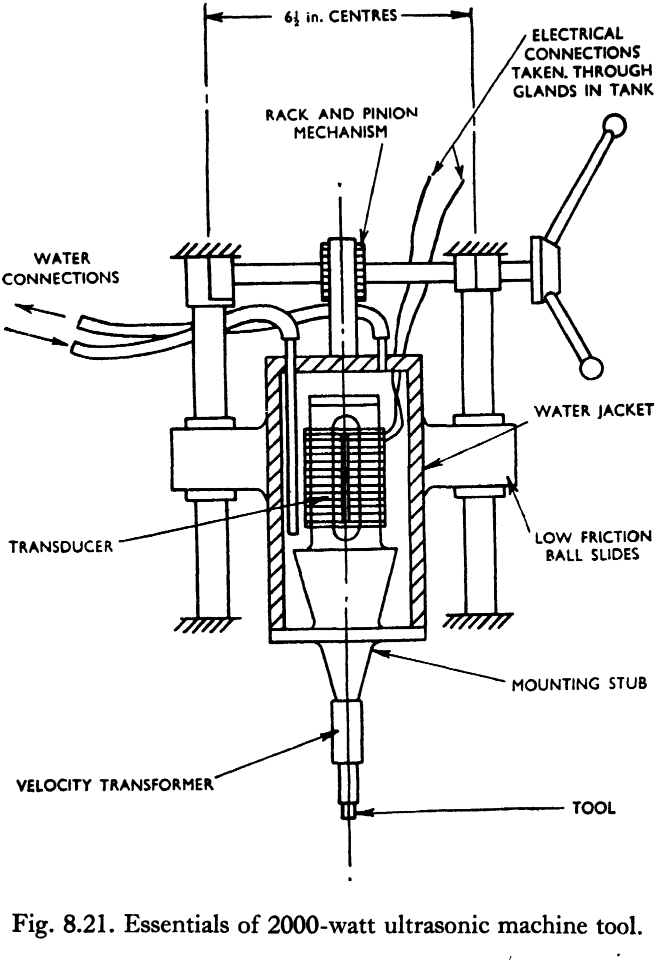

Fig. 8.21. Essentials of 2000-watt ultrasonic machine tool.

In all ultrasonic machining the actual cutting edge is provided by using an abrasive slurry, the particles of which become partially embedded in the tool body made of relatively soft metal. The vibrating tool face is applied lightly to the workpiece, against which it pounds the abrasive material at high frequency. The slurry is applied, either intermittently by hand or continuously by means of a pump, to replace abrasive particles which are used up. The heat generated is negligible and the material is virtually unstressed.

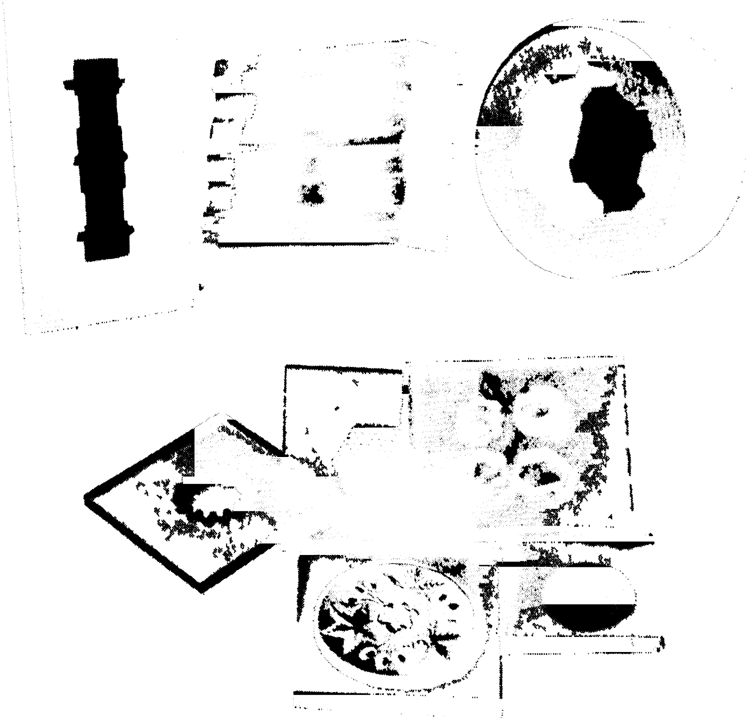

Fig. 8.22. Holes and patterns of various shapes cut in sintered tungsten carbide and glass

Tools for piercing may be given any desired form (Fig. 8.22), and tubular trepanning tools may be used to reduce the amount of material to be crushed. There is no theoretical limit to the depth of hole provided the tool length is arranged so that the complete vibrating system including the tool consists of an exact number of half wave-length sections.

Materials which have been successfully machined by the ultrasonic technique include glasses, most ceramics, mineral stones, precious stones, fused alumina and silica, sintered carbides and brittle metals such as germanium, titanium, tungsten, die steels, and many tool steels. In the majority of common metals not noted for their brittleness cutting rates are generally quite slow, but even here the technique is sometimes of value when shaped holes are required. The maximum cutting speeds obtainable in soft brittle materials such as glass and soft ceramics are of the order of 2 cm/min. Speeds are

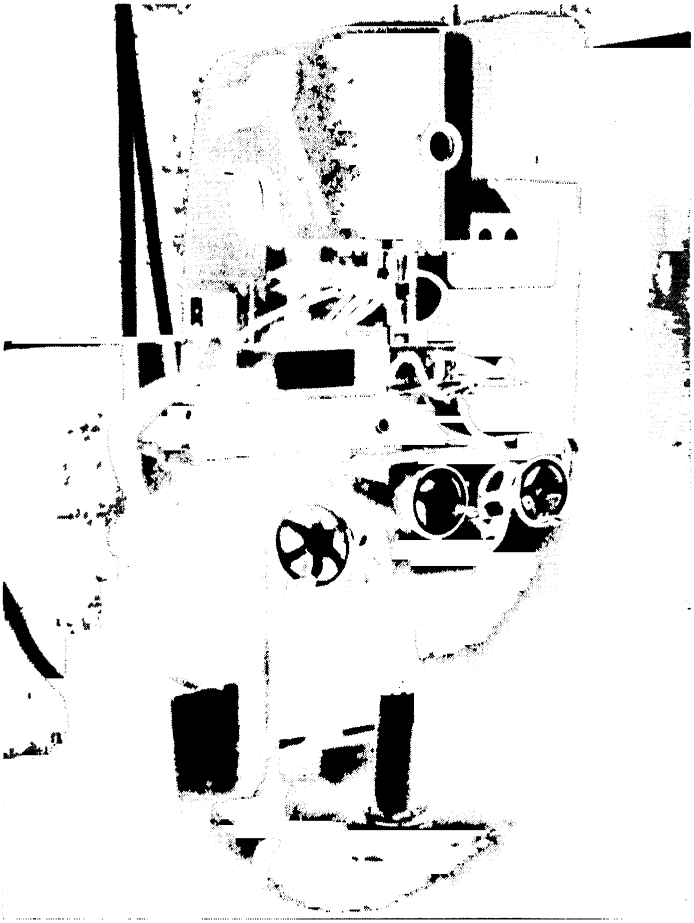

Fig. 8.23. 2000-watt ultrasonic machine tool mounted on a standard type machine base, with movable work-table.

about a factor of 5 less in materials such as fused alumina, germanium, and many precious stones, and a factor of 20 less in sintered tungsten carbide and many brittle steels.

With suitable abrasive powder, a high degree of precision of size and form may be obtained. Dimensional accuracy of the order of 0·0002 in. with surface finish down to 3 or 4 μin. can readily be obtained in most materials. The wear of the tool head itself is relatively slight, except when cutting die steels and sintered carbides, but for high precision it may be necessary to take a roughing followed by a finishing cut.

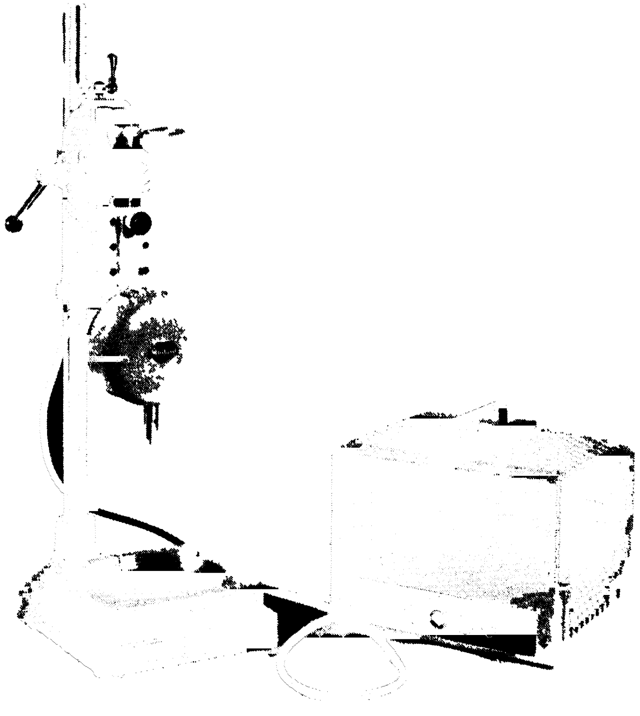

Fig. 8.24. 60-watt bench-mounted ultrasonic drill on precision stand.

The technique has already been widely applied in die-making (extrusion, wiredrawing, stamping, and blanking dies); slicing and multiple-blanking operations in quartz, germanium, and precious stones; profiling and pantograph techniques in glass; in dentistry; and in a variety of special types of machining operations such as the cutting of curved holes and screw threads in brittle materials, to which the technique is readily adapted. Machines for different ranges of work have electrical inputs varying from 20 to 2000 watts. Fig. 8.23 shows a full-size machine tool for general workshop use, input power 2000 watts and Fig. 8.24 a 60-watt drill. A sketch of the basic vibrator for this machine is given in Fig. 8.21.

Factors affecting performance. Cutting rates are found to increase, proportionally, less than the *rate of vibration*, perhaps owing to the decreasing time available for grain replacement and waste removal. It increases at a higher rate proportionally than the *amplitude of vibration*, but too high an impulse per blow may cause spraying of the slurry. For efficient circulation of abrasive and removal of waste the abrasive grain size and the peak-to-peak oscillatory movement of the tool should be of the same order.

Increasing the mean or *static load* upon the drill at first causes a rapid increase in cutting rate, but a broad peak is reached after which this decreases. Too large a load upon the drill will reduce the amplitude of vibration and may stop the motion completely. The optimum load, from a few ounces to several pounds, will vary according to the job, and with the area and the shape of tool.

The liquid element of the slurry carries and distributes the abrasive, removes the waste products, and cools the workpiece. Violent cavitation is produced over the tool face, with the liberation of absorbed gases as minute bubbles, and strong local currents are formed in the slurry across the cutting face and between the lateral faces of the drill and hole, their intensity varying with end and side clearance, the rate and amplitude of oscillation, etc. Cavitation aids the flow of abrasive particles and increases the cutting rate. The contribution made to the cutting action at the face of the tool by cavitation erosion and by the abrasive action of the streaming slurry is very small, but the streams tend to take up definite positions in the lateral clearance space, and produce local scouring of the workpiece, with reduction of surface quality. The use of flutes upon the drill, where permissible, may increase the cutting speed by increasing the supply of cutting material to the face.

Examination of the particles of work material clearly shows these to have been formed by a chipping process, unlike the tiny spheroids formed during spark-erosion by the process of local intermittent evaporation followed by condensation.

The damping of the vibrations due to the viscosity of the slurry itself has little effect for simple tools and short holes, but for tools of large side area—as for the cutting of splines, etc.—the effect may be considerable. When drilling very deep holes viscosity may greatly retard the passage of slurry and waste in the side clearances. To obviate this the shank of the tool may be reduced behind the face, but if the reduction of area is large, considerable energy may be transmitted from the back of the head to the liquid unless a pad of vibration-absorbing rubber is placed over this rear face.

The Tool. The tool may for most purposes be made from a tough material which does not chip easily. It always sustains some wear, so that the cost of replacement of intricately shaped tools has to be considered. For such tools, or for high precision, special materials may be needed. The ease with which abrasive grains become embedded and held in the softer materials has less influence on cutting rates than might be supposed. For example, copper and stainless steel are about equally effective, as are mild steel and tungsten carbide. But the rates of wear of the tool material may be very different.

Secure attachment of the tool to the transformer stub is essential. This junction must be able to transmit vibration efficiently and also to allow exact alignment of the tool. Brazing and hard soldering, separately or combined with screwed joints, have been used. Screwed or tapered joints allow easy interchange and replacement but are weak mechanically. The tool and transformer stub must be designed together to produce a structure mechanically tuned at the transducer resonance.

The Abrasive. The abrasive depends for success not only on hardness, but also on the shape of its particles, the number and durability of the irregularities which form the cutting edges, and the nature of the mode of fracture. The particle size should be chosen to suit the cutting rate and surface quality required. For rapid cutting the grain size should be as a large as possible, having in mind the limitation imposed by the peak-to-peak motion of the tool face. The particle size should always be kept small in comparison with the minimum breadth of blade tools used for slotting or of the wall thickness of trepanning tools.

Boron carbide is the hardest of the carbide abrasives and is largely used to cut tungsten carbide, hardened steel or jewel stones. It breaks easily under pressure and is, therefore, specially valuable for polishing and lapping. The specific gravity being low, the grits remain in suspension for long periods. Black carborundum grains are not so hard as boron carbide, but break by small-scale chipping and maintain good cutting action. Carborundum is suitable for use on all but the hardest of the brittle materials and is relatively cheap, but the grains are less easily wetted and separate from the slurry rather more rapidly than does boron carbide. Alumina abrasive is cheap and suitable for most glasses and ceramics, but is too soft for use on the harder materials.

Feed of the slurry may be by hand or pump; for large work several jets may be arranged. Hollow tools enable it to be pumped centrally to the work face. The supply must be constantly maintained or the cutting speed will be reduced, and the slurry at the working-face may dry out, with serious heating, and possible cracking of very brittle materials such as glass. Care should be taken that the slurry and waste do not clog tool clearances, pipework, etc.

The liquid component of the slurry fulfils several functions. Water has the best all-round properties and gives a cutting speed some three times greater than with lubricating oils and at least 50 per cent greater than with kerosene, or other thin oils.

Tables 8.1–8.3 indicate the effect on cutting speed of different workpiece materials, abrasive grit type and size, and tool areas.

TABLE 8.1. CUTTING SPEEDS IN VARIOUS BRITTLE MATERIALS

(H-section boring tool ½ × ½ in. overall with member $\frac{1}{16}$ in. broad)

Material	*Comparative cutting speeds using the following abrasives*			
	Boron carbide			*Silicon carbide*
	100	220	400	100
Soda glass	100	90	77	85
Hysil	73	66	54	
B9 Borosilicate glass	86			
Ferroxcube IIIC	37			34
Magnadur (demagnetized)	32			
Quartz crystal	57			
Fused alumina	19			
Synthetic sapphire	19			
Synthetic ruby	18			
Flint stone	72			
Barium titanate ceramic	110			109
Ceramic 507	38			35
Garnet	58			
Felspar	40			
Spinel	48			
Slate	67			
Micalex	240			200

TABLE 8.2. CUTTING SPEEDS IN INDUSTRIAL CERAMICS

(Circular boring tool ¼ in. dia.)

Material	*Comparative cutting speeds using the following abrasives*					
	Boron carbide		*Silicon carbide*			*Alumina*
	100 *mesh*	400 *mesh*	100 *mesh*	400 *mesh*	600 *mesh*	220 *mesh*
Chemical porcelain	70	14	53·5	11	2	25
Temperadex	60	10	45	7·5	–	20
Faradex	55	7	41	5	–	2
Vulcanex	190	51	168	44	2	62
Z.Z. Porcelain	90	32·5	75	26	2	10
H.T. Porcelain	45	24	41	22	–	8
Frequentite	47·5	27·5	45	26	–	20
Soda glass	100	45	80	37	6	70

TABLE 8.3. RELATIVE CUTTING SPEEDS IN METALS

(H-section boring tool ½ × ½ in. overall with member $\frac{1}{16}$ in. broad)

Material	*Comparative cutting speeds using the following abrasives*						
	Boron carbide Mesh No.			*Silicon carbide Mesh No.*100	*Alumina Mesh No.*220	*Sand (Grit size* 0·012″)	*Diamond powder (Grit size* 0·001″)
	100	220	400				
Soda glass	100	90	77	85	65	47	90
Brass (Common yellow)	6·6	5·6					
Die steels:							
(i) K.E.672 (R.66)	1·4	1·3					
(ii) C.S.K. (R.62)	3·9	3·6					
(iii) K.E.672 (R.61)	2·2	2·1		1·48	0·1	0·1	
(iv) K.E.672 (R.58)		1·7					
Stainless steels:							
(i) 18% Cr, 8% Ni, 0·1%C	2·1	1·9					
(ii) 3·5% Cr, 8·4% W, 0·35% Va, 0·3% C	1·2	1·1					
Carbon-chrome steel bearing (heat treated)	1·4						
Sintered tungsten carbide (R.76)	4·1	3·5		2·55	0·2	0·2	4·3
Tungsten	4·8	4·3					
Stellite	4·0	3·7					
Germanium single crystal	31			28			
Titanium	4·0						
Beryllium	7						

Stress Effects. An important advantage of this technique is that under normal operating conditions it leaves no residual mechanical stresses in the material being cut. This is shown by the fact that even in the most brittle easily-fractured materials, the pieces chipped off are small even compared with the abrasive grit dimensions, showing that the stresses communicated to the workpiece must be very localized. Photoelastic examination of cuts in glass has failed to show any residual stress effects.

In this connection it is important to stress the importance of the liquid coolant. If for any reason the abrasive powder is allowed to dry out, high temperatures may be developed at the tool tip and thermal stress will be produced in the workpiece with the possibility of fracture.

In the drilling of through-holes in glass etc. chipping at breakthrough may be caused. This may be prevented by drilling through the workpiece into a backing plate which may be of the same material as the workpiece and rigidly bonded to it. Drilling should be continued well into the backing material as the cutting edges of the tool may well have become rounded in use.

Tool Wear. The longitudinal wear obtained in tools is found to be least for tough steels and greatest for brittle materials, except where the tool is harder than both the abrasive and the work, when tool hardness is the important variable. Operating on glass using a boron carbide abrasive the ratio of tool wear to stock removal is about 0·1 per cent for tools made of tungsten carbide and 1 per cent for mild steel tools. When cutting tungsten carbide itself, these figures are increased to 110 per cent and 88 per cent.

If there is any lateral component of vibration in the tool, rapid side wear may occur. Side wear by impact will be superimposed on that by abrasion. The grinding face of the tool becomes cumulatively rounded, and will require periodical regrinding to restore correct cutting action.

Machining Accuracy. As the process is essentially dependent on abrasive being fed to the working-face between the workpiece and the tool, a slight taper is bound to be formed due to lateral wear of both workpiece and tool. In boring, the hole at entry will be slightly larger than the original tool size, but if the hole is deep the wear of the tool itself may result in a decrease in hole size to less than that of the unused tool. In through-holes the latter effect may be corrected by the use of a long tool which is fed through the hole an extra distance of at least the depth of the cut. The amounts of oversize and taper will vary with tool and workpiece material, grit size and time of operating.

In piercing operations, side clearance rapidly increases at first with depth, but with further penetration becomes nearly constant at a value a little larger than the grain size. Repassing with a fresh tool to remove a few thousandths of an inch of material will sometimes be necessary. Oversize of the order of 0·001 to 0·016 in. may be encountered, and cores from trepanning tools, having a reversed taper, will be similarly undersize.

For high accuracy it will be necessary to carry out the machining operation in several stages. The initial roughing cut can be done at high speed, using a slightly undersized tool and a coarse grit. This is then followed by one or two sizing operations with tools of increased size and finer grits. Even with coarse grits the oversize can usually be predicted to within ± 0·002 in. which is sufficient for many purposes, and this can therefore be achieved in a single operation. Alignment and rigidity of the tool and machine are clearly important, especially during repassing (or sizing) operations with fine grits.

Surface Finish. The quality of the surface finish is closely related to the abrasive grit size. Using boron carbide on glass the c.l.a. roughness may vary from 200 micro-inches for 100-mesh grit to 50 when a 600 mesh is used. For tungsten carbide about one-quarter of these values will be found. The roughness produced by the face of the tool is generally less than that at the sides of the cut. In addition to the general roughness of hole bores, local wear due to regular streams of slurry flowing under the influence of cavitation may produce furrows of a depth roughly corresponding to the grain size and increasing with cutting time. Lapped surfaces are free from such blemishes.

Special Applications. An important application of the ultrasonic machining technique is in the field of die-making. All the materials used—hardened steels, sintered carbides, sintered alumina and diamonds—are brittle enough to be machined rapidly by this method. Complex blanking or extrusion dies can be cut out rapidly in one piece, using inexpensive boron-carbide abrasives. Dies for medallions etc. in tungsten carbide or the etching of patterns can be copied from prototype. The cutting being at first confined to a small number of high points, it is often necessary to use at least two replicas for roughing and finishing. Wiredrawing dies may be made by suitable combinations of piercing, lapping and repassing operations. In certain cases the tool head may be operated at an appreciable distance from the transducer, using a flexible steel wire to transmit the energy.

A valuable application of multiple slicing and blanking techniques is in the manufacture of transistors; the materials used, germanium and silicon, are brittle and easily machined by this method. The same applies to the production of jewel bearings for watches and instruments, where ruby, sapphire and agate are used.

The production of tapped holes and threads in brittle materials is a very interesting recent application. In these cases the tool is a piece of tapped tube or threaded rod in mild or medium-tough steel fixed to a flexing attachment of the drill horn, as already explained. Taps and dies can be produced rapidly and cheaply in sintered carbides or Sintox.

Advantages. Where the ultrasonic vibration method is in competition with others, the special merits and disadvantages of each must be carefully assessed.

Points in favour of the ultrasonic method are the ease with which accuracy and good surface finish can be achieved. No heat is generated in the work and consequently no changes are introduced in the physical structure of the material. The equipment is safe to handle and requires skilled labour only in the making and setting of the actual tools: these are, however, cheaply made in a soft metal and tool wear is small. Cheap abrasives are used and expensive diamond powder is needed only for drilling diamond. The technique is applicable to all brittle materials and is not limited by any other physical property of the substance, including hardness. The method stands alone where non-conducting materials are to be machined—such as glass, ceramics or jewel stones.

For Bibliography see end of book.

CHAPTER IX

SCREW THREAD PRODUCTION

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EXTERNAL SCREW THREADS

Thread Cutting. External threads are usually produced by either *Cutting*, *Rolling* or *Grinding*. The most commonly used methods of screw thread cutting are:

(*a*) *Single point cutting tool in a lathe*, the tool being traversed along the rotating work-piece at a rate to produce a thread of the required lead; the thread form is obtained by repeated passes of the tool and using progressively deeper cuts.

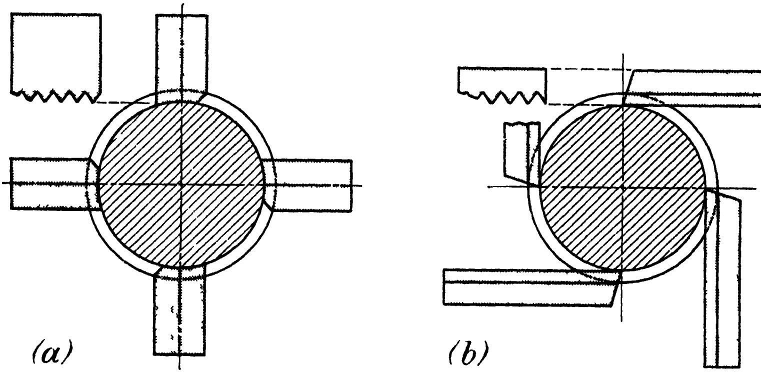


Fig. 9.1. Cutters or chasers. (*a*) Radial. (*b*) Tangential

(*b*) *Adjustable diehead with removable chasers*, the latter (Fig. 9.1) are multi-toothed and cut several threads simultaneously. It is usual for the chasers to open at the end of the cutting operation to enable the diehead to be quickly and easily returned to the starting position without having to run the work-piece in the reverse direction, to screw the diehead off the work. The diehead may be traversed by a lead screw, or may be self-leading, in which case the chasers and the screw being produced together impart the requisite traverse to the diehead, as when cutting an internal thread with a simple tap. It is usual to complete the screw in one pass of the diehead.

(*c*) *Single-ribbed thread milling cutter.* This method is similar to using a lathe but the lathe tool is replaced by a milling cutter of related cross-section having its axis inclined so that it is in a plane parallel to the helix angle of the thread. The cutter is fed in and traversed at the correct speed along the slowly rotating work-piece, the screw being completed in one or more passes of the cutter, according to the rigidity of the work-piece, the amount of metal to be removed etc.

(*d*) *Multiple-thread milling cutter.* This cutter is a series of annular grooves of the required profile, in effect a number of single cutters spaced out at the required pitch, the total length being slightly greater than the length of the thread to be cut. The cutter, whose axis is parallel to the axis of the work-piece, is fed in to the required depth and traversed along the slowly revolving work-piece, the screw being completed in slightly more than one or two revolutions of the work.

Some factors which bear on the quality of the screw produced, are common to all the above methods. The accuracy of the thread profile is dependent on the accuracy of the profile of the tools or cutters used, and, when they are of the multi-tooth type, on the accuracy of the spacing or pitch of the teeth. When the tools are traversed by a lead screw the accuracy of the lead is primarily controlled by the correct relative speeds of the work-piece and lead screw and the accuracy of the lead screw itself. Other factors are the precision of operation of the whole mechanism over the length of the traverse, and the accuracy of alignment.

The rake angles of the tools or cutters used, the speeds at which the cutting is done, and the supply and nature of the coolant used all have a great bearing on the quality of the work produced. It is essential that the tools are properly ground and kept in first-class condition.

Of the above methods of screw cutting the most versatile is the single point tool in the lathe. Any form of thread can be cut with single or multiple start, and of any length within the capacity of the machine. The degree of accuracy which can be achieved is of the highest order; the tooling is simple and the tools are easily maintained. The main disadvantages are the low production rate and the high degree of skill demanded of the operator when components must be held to exacting tolerances.

The diehead, whilst not so versatile as the single point tool, has many advantages. It is capable of high rates of production under the control of unskilled operators and is readily adaptable for use on multi-spindle automatics and other types of turret lathe. The degree of accuracy obtainable is suitable for a very large percentage of commercial work. The tooling, whilst still simple, is slightly more involved than for the single point method. The production of the chasers themselves is highly specialized, but maintenance is simple, given the necessary grinding fixtures. The geometry of the throat or leading edges of the chasers is of paramount importance when producing accurate work with a good surface finish, and also in prolonging the cutting life of the chasers themselves.

A greater degree of accuracy can be achieved when the diehead is traversed by a lead screw than if it is self leading, when the thread may be distorted by having to provide the traverse movement; this is most apparent on the first two or three threads of the component, and with soft free-cutting materials. The diehead method may become uneconomical when cutting large diameters or coarse pitches, or where a very high degree of accuracy is demanded. Difficulties may also be encountered when trying to cut full threads close up to shoulders, etc.

The single ribbed milling cutter method of production is particularly applicable to very coarse threads where a large quantity of metal has to be removed, and to multiple start threads, as the stresses involved may be much less than with a single point tool, thus conducing to greater accuracy.

The multiple-thread milling cutter is most suitable for short lengths of thread where the helix angle of the thread is small, that is on large diameters with comparatively fine threads. This method also has its advantages where the thread must start in a fixed angular position relative to some other feature of the component. High production rates are possible as the operation is completed in slightly more than one or two revolutions of the work-piece, and a high degree of surface finish is readily achieved. This is essentially a mass production method, otherwise the high initial cost of the tools would never be justified.

Thread Rolling. In this method the thread is produced by the pressure of a forming tool or die against the rotating work-piece. No material is removed from the blank but metal from the root is caused to flow outwards to form the crest of the thread. The very nature of this forming operation causes the grain structure of the material to follow the contour of the thread profile. Photo-micrographs of rolled thread components show that the fibres of the material are compressed at the root and flow outwards in the form of a curve roughly following the flank and crest of the thread. This grain flow is in marked contrast to the grain structure of components where the thread is produced by cutting, here the fibrous structure of the material is normally parallel to the axis of the screw, but broken or interrupted by the thread profile. The grain flow of the rolled thread produces a superior finish and a work hardened and burnished surface. A screw produced in this manner will be stronger than a a screw of the same size and material produced by other methods. This increase in strength leads to a great increase—up to 75%—in the resistance of the component to fatigue.

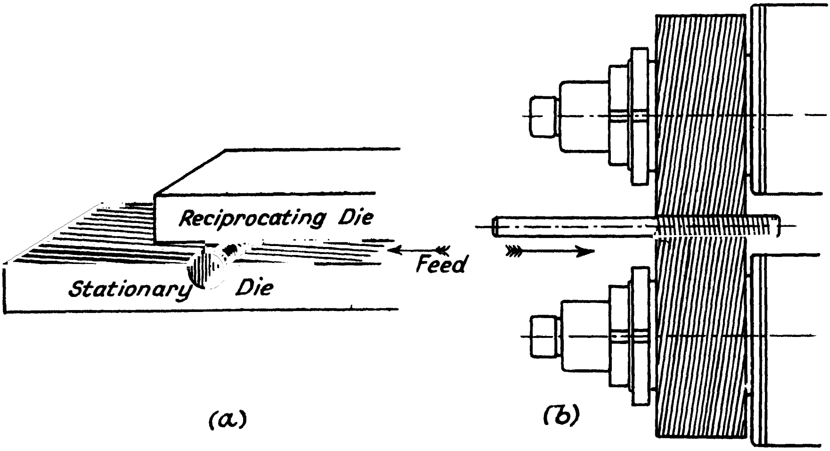


Fig. 9.2. Principle of thread rolling. (*a*) with flat dies, (*b*) with cutters or chasers

(*BSA Tools Ltd.*)

There are two basic methods of thread rolling, one using flat dies and the other using circular dies or rolls. (Fig. 9.2.) With flat dies, one is stationary and the other has a reciprocating movement parallel, or nearly so, to it. The blank to be threaded is inserted across the thread form at one end of the stationary die and when the reciprocating die takes control the blank is forced to roll between the working faces of the dies until it is ejected with a fully formed thread.

The working surfaces of these dies (Fig. 9.3) have shaped parallel grooves which are set at an angle to the line of travel of the blank whilst it is being rolled; this angle is equal to the helix angle of the thread to be produced. The form of the grooves, when measured in a plane perpendicular to their own direction, is approximately the form to be produced on the component, but to ensure that the form is correct when measured in a plane parallel to the axis of the component as it is being rolled, the included angles of the grooves are made smaller and their spacing or pitch shorter. This lessening of the angles and pitch is directly proportional to the cosine of the helix angle of the component thread.

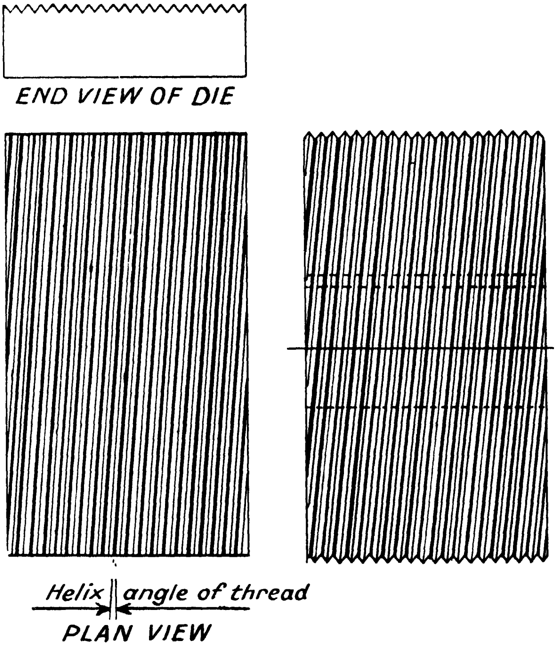


Fig. 9.3. Thread rolls: *left* flat die, *right* circular

Machines using circular dies or rolls are built either to use two rolls and a work rest (Fig. 9.4) similarly to the centreless grinding machine, or three rolls arranged in a cluster, the third roll being used to replace the work rest of the two-roll machine. Both types of machine are capable of producing threads in either of two ways, plunge rolling or through rolling. With plunge rolling the total length to be threaded must be less than the width of the rolls; with through rolling it may be greater.

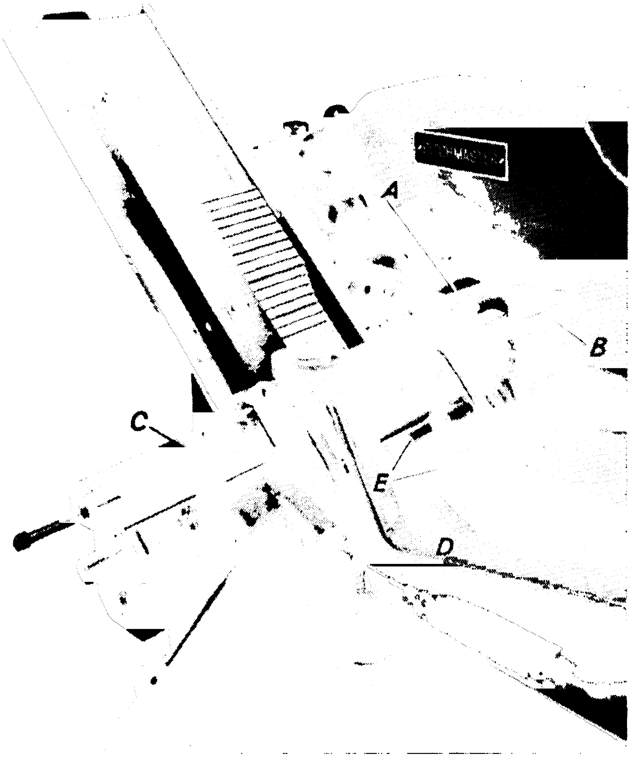


Fig. 9.4. Automatic feed on Pitchmaster thread-rolling machine

A: Thread roll rotating on fixed centre;
B: Thread roll driven on slide;
C: Feed and withdrawing slide actuated by control arm *D*;
E: Channels for receiving finished work which is tipped into the chute beneath.

(*Drummond Asquith Ltd.*)

Plunge Rolling. For this method the work-piece is placed between the rolls, where it is supported by the work rest or by the third roll. The rolls, which are all rotating in the same direction, are then moved inwards towards the centre of the work-piece. The work-piece is thus made to revolve in the opposite direction to the rolls and the component material is caused to flow into the required thread form. After a predetermined time, when the screw is finished, the rolls are moved apart.

While rolling is in progress it is essential that the axial movement of the component is minimized otherwise severe damage to the rolls or component, or both, may result. This axial movement of the component, sometimes referred to as *creep*, is governed by the ratio between the size of the roll and the size of the component.

THROUGH ROLLING. Here the component is allowed to move axially, the leading end or throat of the rolls is modified, and the rolls are set at a correct distance from each other for the size of the component, which is allowed to feed through the rolls in the same manner as in "through grinding" on a centreless grinding machine. On the periphery of the rolls is a multi-start thread whose pitch and form are the same as that to be produced on the component, but of the opposite hand; for right-hand components the rolls have a left-hand thread and vice versa. The diameter of the rolls is a function of the effective diameter of the component and is best established empirically as it is the controlling factor in the elimination of creep in plunge rolling and the rate of feed or traverse of the component in through rolling.

QUALITY OF ROLLED THREADS is mainly dependent on the following factors:

The size of the blank before rolling will be approximately the effective diameter of the finished screw. When rolling full form threads, as apart from threads with truncated crests, this size controls that of the finished thread. If the blank is oversize, so will the thread be, and if a reduction of the thread is attempted by closing the rolls, damage will be caused to the rolls and component. When rolling truncated threads, the threads in the rolls are not completely filled with the component metal and the size of the blank controls the amount of truncation produced, hence the resulting outside diameter of the thread. From this it is obvious that the tolerances of the thread to be produced govern the tolerances to which the blank must be held prior to rolling.

The pitch relationship of the rolls or dies. It is obvious that if this were seriously wrong, the rolling operation would be trying to split the thread and it would not be possible to produce a satisfactory component. Small errors do not actually prevent production, but may cause marked shortening in the life of the rolls.

The chamfering at the end of the thread on the component: this reduces the tendency for the material to flow over the end of the component during the rolling operation, as does any recess where the thread finishes. It also helps to prolong the life of the rolls.

Comparing the two methods of rolling—with flat or circular dies —it would be fair to say that the circular die could be likened to a flat die of infinite length, so that with circular dies the penetration can be spread over a greater time, tougher materials can be processed, and more precise components produced. However, the flat die method will produce satisfactory components over a very wide range, particularly in more ductile materials.

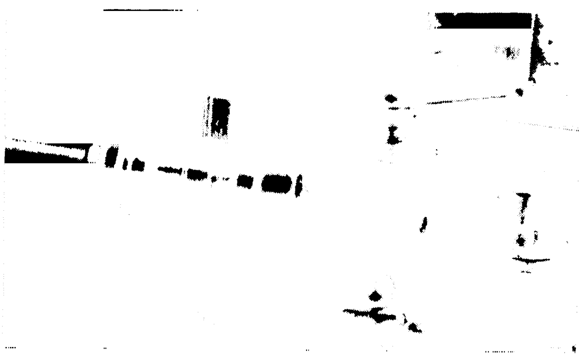


Fig. 9.5. Thread Grinding; formed wheel is behind work-piece

The increase in strength of the material brought about by thread rolling makes it a method very suitable for the production of bolts and studs which are to be highly stressed. But the process is not economical for small quantities, owing to the high initial cost of the dies. The speed and simplicity of operation make it well suited for automatic feeding, hence for mass production.

Thread Grinding. This is basically similar to thread milling, the milling cutter being replaced by a grinding-wheel, and here again there are two methods which can be employed: the "pass over" method, where a single or multi-ribbed wheel is traversed along the total length of the screw being produced, (Fig. 9.5) or the "plunge grinding" method where the multi-ribbed wheel is wider than the length of thread to be ground, which is completed in slightly more than one or two turns of the work.

The grinding-wheel can be formed to the shape of the thread profile either by diamond dressing or by crushing. Crushing, whilst not as accurate as diamond dressing, is a much quicker method and is done by forcing a hardened steel crushing roller into the grinding wheel as it revolves slowly. The crushing roller has a series of annular grooves of the same form and pitch as the thread to be produced, around its periphery. These grooves are not a thread as they have no lead, but they are sometimes referred to as a "still thread".

The diamond-dressed wheel is used where the highest degree of precision is called for, and for extra fine pitches which cannot be crush-formed. The crushed wheel is used where the tolerances on the thread profile are slightly wider, though it is still possible with such dressing to produce components to a very high degree of accuracy.

The grinding-wheel can be set over to the helix angle of the thread, provided that its full width will pass over the total length of thread. Where as in plunge grinding or grinding up to a shoulder or into a narrow recess, this will not happen, such setting over would introduce pitch error into the thread over which the full width of wheel has not passed. In such cases it is necessary to apply a slight correction to the form, and to make the ribs on the wheel slightly narrower as they will produce a gap in the component wider than themselves due to a slight generating action caused by the grinding wheel running in a plane not parallel to the helix of the thread.

Thread grinding enables components to be screwed which have previously been heat treated, thus eliminating distortion which would take place if cutting preceded heat treatment. This makes it ideal for the production of tools, gauges and precision feed screws etc. The pass-over grinding method using a diamond-dressed wheel gives the highest accuracy, and gauges are produced in this manner. The crush-formed wheel will cut faster than the diamond-dressed wheel and some very high rates of metal removal are possible. All roughing is usually done with such a wheel, but sufficient accuracy is easily achieved to make this type of wheel dressing very suitable for finishing a very wide range of products, notably in the bulk production of taps. The plunge grinding method is used for rapid cutting of short lengths of thread on components of robust construction such as hardened studs.

Accuracy and quality with thread grinding are influenced by the same general considerations as with cutting a thread; it has of course the advantage inherent in all grinding, in the maintenance of narrow tolerances on diameters. The correct grinding-wheel for the type of work in hand is essential, and the value of experimenting to this end cannot be over-emphasized as it influences production speed, surface finish, production between dressings, and the life of the dressing tool whether diamond or crusher.

External Thread Cutting Methods Compared. Thread-cutting, rolling and grinding can only be compared in the most general terms, as each method is capable of many minor refinements. Each has its applications and range of products to which it is best suited, but these ranges cannot be rigidly defined.

Grinding is the most versatile method of them all, as threads of any form, with the single exception of the square thread, can be produced on any material whether it has been heat treated previously or not, to the highest degree of accuracy and surface finish. *Cutting* is equally versatile as to the form of thread, but this must be produced before heat treatment. Accuracy comparable to that achieved by grinding can be achieved by cutting, but a high degree of surface finish not so readily. *Rolling*, while fully adequate for many purposes, will not produce the ultimate accuracy which can be achieved by grinding or cutting. The degree of accuracy possible is very largely controlled, away from the actual rolling operation, in the manufacture of the dies, in the production of the component blanks and the initial setting of the machine, consequently the rolling operation calls for no skill on the part of the operator; it can easily be made automatic and is very fast. Not all materials of course are suitable for this type of flow forming, and it is economic only for large quantities.

INTERNAL THREADS

Tapping. The vast majority of internal threads are produced by tapping, and though the taps used to produce the smaller threaded holes are well known and apparently simple, it must be remembered that they must fulfil the same function as the more elaborate screw-cutting lathe, i.e. metal must be removed from the workpiece by a series of cuts of increasing depth, and the cutting edges must move axially with respect to the work-piece at the correct rate of travel so as to produce the required helix.

The cutting edges of a tap are provided by milling a number of flutes equi-spaced around its periphery, and the periphery is threaded to provide cutting edges with the correct profile and the requisite traverse. The rake angles necessary for cutting are provided by the shape of the flute (top rake) and by relieving the lead or taper portion at the front of the tap (front rake). The flutes must also provide temporary but adequate storage space for the swarf as it is produced, but be of such a design that the torsional strength of the tap is sufficient to withstand the cutting load. It is apparent from the above that the correct design of the flutes is of great importance (Fig. 9.6).

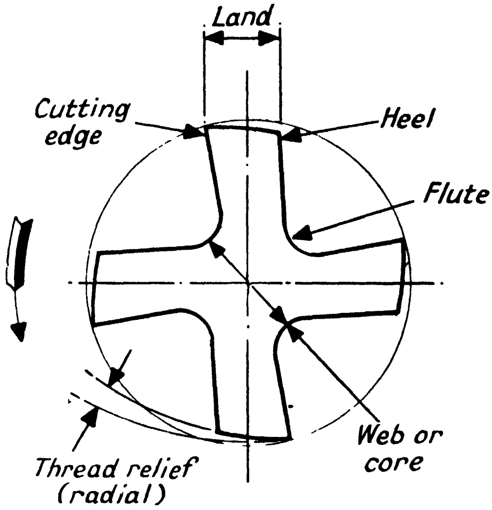


Fig. 9.6. Tap flute terms

Whilst the majority of all taps have straight flutes, helical flutes are also used, of either hand of spiral (Fig. 9.7). These are advantageous when the material being tapped tends to produce a continuous chip in the form of a curl or spiral, when right-hand spiral flutes will bring the chips to the mouth of the hole, which is helpful in blind

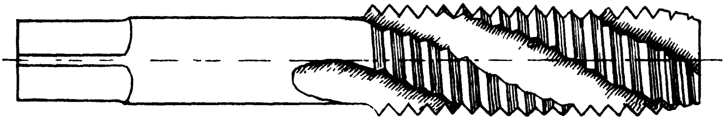
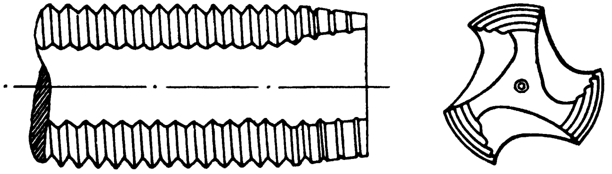


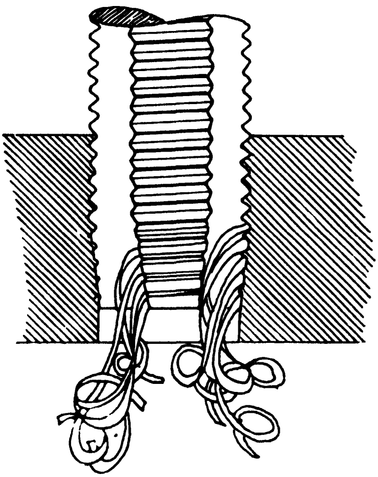
Fig. 9.7. Helical fluted tap

hole tapping. Left-hand spiral flutes as on "gun nosed" taps, where they are cut steeply inclined at the entering end, will drive the chips down the hole in advance of the tap (Fig. 9.8) and so avoid choking the flute, which may lead to the tap seizing in the hole. Such taps are largely used for through holes.

One further important point about the flute is the rake of or the trailing edge of the land. When the tap is reversed out of the



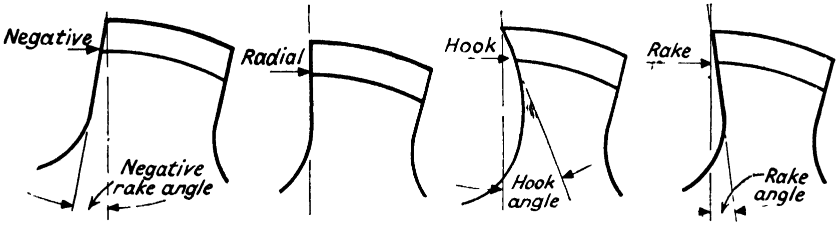
GUN TAP END VIEW



GUN NOSE TAP
Chips shooting ahead of
tap in through hole

Fig. 9.8. Spiral pointed or gun nose tap

finished hole this face of the flute must sweep before it any swarf which remains in the hole to allow the tap to come out freely, but it must not cut at the parent metal or an oversize hole will result. For economic and efficient production, the flute form (Fig. 9.9) is carefully designed in relation to the material being cut. *Negative Rake*



NEGATIVE RAKE RADIAL HOOK RAKE

Fig. 9.9. Tap flute forms

is used for brass and certain special purposes; *Radial* is used for soft brass and fibre; *Hook* is used for aluminium, copper, duralumin, gunmetal, cast iron, magnesium alloys, monel metal, nickel silver, rubber, chromium, mild steel, manganese, nickel and stainless and tungsten steels; and *Rake* for bakelite, hard brass, manganese and phosphor bronze, ebonite, fibre, cast and malleable iron, cast steel and for manganese, molybdenum, tool, tungsten and vanadium steels.

For the machine production of nuts, taps are used having a shank smaller than the minor diameter of the threads. The nuts, after tapping, feed over the shank and can then be removed, or automatically ejected. This avoids the necessity of reversing the tap after the nut is threaded, thus improving accuracy.

The length of the taper lead of the tap and the number of flutes are very important in successful tapping as they determine the

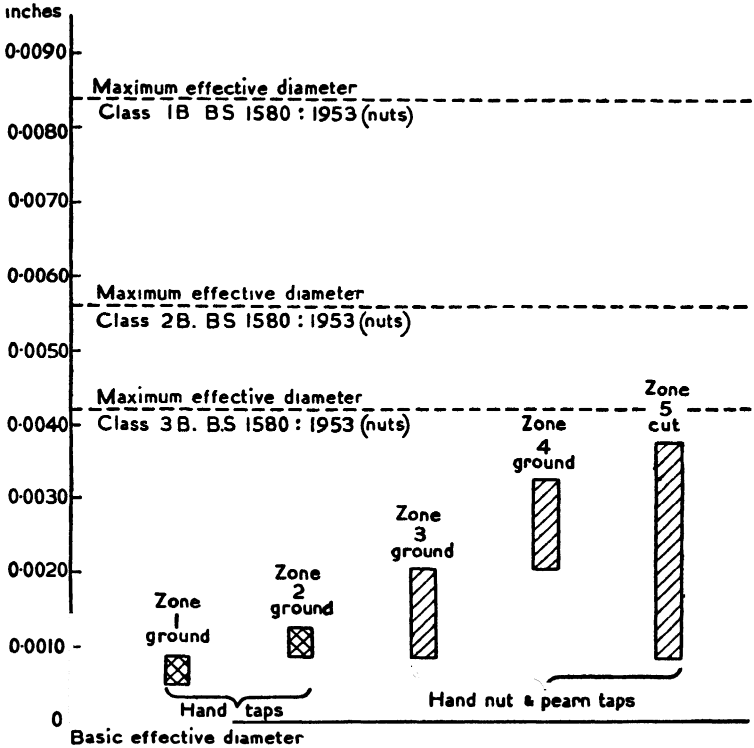


Fig. 9.10. Diagram showing tolerance zones of taps; the example relates to ½ in. UNF thread

number of teeth involved in cutting, hence the tooth load. It does not follow in every case that the longer the length of lead the lighter the load on the tap; in certain materials the shorter the lead the easier is the tapping operation. Standard taps are available with three different lengths of lead, stated approximately by the number of pitches or threads over which it extends: *Taper*, 9–10 threads; *Second*, 4–5; and *Plug*, 1–2. The second and plug (or bottoming) leads are those in most common use in machine tapping, but no hard and fast rules can be laid down for the length of lead, which is best arrived at by experiment, being guided by the limits imposed by the component specifications, such as the depth of full thread in a blind hole.

Standard taps are available for all the recognized thread systems in five zones or tolerance bands, zones 1–4 inclusive having ground threads and zone 5 cut threads. To illustrate how these tolerance bands are disposed, the working tolerances for ½″ B.S.F. threads are here reproduced by permission from B.S. 949, Part 2, 1954 (Fig. 9.10).

This range of tap sizes allows appropriate standard taps to be capable of producing the majority of internal threads which are called for commercially.

Factors in Effective Tapping. First, the hole to be tapped must be of the correct size. A Whitworth screw thread with 75% of the designed thread height has 95% of the strength of a full thread but needs only about a third of the power to cut. This should be remembered when considering the size of tapping drill or punch. The tap and hole must be concentric and the axis mutually aligned; any misalignment will result in bell-mouthed and oversize components and tap breakage through overloading. When tapping blind holes, clearance should be provided where possible in the bottom of the hole to accommodate swarf, and to ensure that the tap does not hit the bottom; and it is usual to employ a special tapping chuck which trips at excessive pressure, or reverses on reaching the bottom.

The speed at which the tap is driven is very important and the best can only be established by trial and error. Increases in speed can lead to increased tap wear out of all proportion to the small amount of time saved. As a very rough guide, the coarser and longer the thread to be tapped the slower must the tap be run. In a variety of components and some types of materials, if the tap is running at too high a speed for smooth cutting, the hole will close in so that the "go" gauge will not be accepted. This phenomenon is most noticeable on thin-walled components, but it can occur where the material around the hole would appear to be of a section sufficiently robust to withstand the cutting stresses without appreciable elastic deformation.

The most accurate results are obtained where the traverse of the tap is controlled by a lead screw or other suitable mechanism as this obviates the tendency of the tap to cut into one flank of the thread and so produce a thin thread as it pulls itself into the hole. When the tap is self-leading it is better held in some type of tapping head which can absorb small and intermittent differences between the correct rate of traverse and the rate at which the operator manually traverses the drill spindle or lathe turret in which it is held. If the tapping is done on a vertical drilling machine, better results can often be obtained if the spindle and counterbalance weight or spring are in a state of balance, rather then when as is usual the counterbalance is heavy.

The correct cutting lubricant is essential, and generally straight oil rather than soluble will give the best results in both quality of component and tap life. However, here again it is not possible to be dogmatic as conditions vary so widely.

Some typical data relating to the tapping of various materials are summarized in Table 9.1.

TABLE 9.1. TYPICAL TAPPING DATA

Material	*Cutting Speeds Ft./min. high speed steel*	*Lubricant*	*Cutting Angle and Rake Type*
Aluminium	70–90	Paraffin and Lard oil or light oil	10°–16° Hook
Bakelite	50–70	Dry	3° Neg. to 3° plus Rake
Brass Soft	80 upwards	Soluble oil or light oil	Radial or Negative
Hard	60–100	ditto	Radial to 5° Rake
Bronze Mang.	35–45	ditto	5°–8° Rake
Phos.	30–40	ditto	8°–12° Rake
Copper	70–90	Paraffin and Lard oil or light oil	15°–25° Hook
Duralumin	70–90	ditto	10°–16° Hook
Ebonite	50–60	Dry	Radial to 5° Rake
Fibre	50–80	Dry	ditto
Gun metal	50–60	Paraffin and Lard oil or light oil	5°–8° Hook

TABLE 9.1—*contd.*

Material	*Cutting Speeds Ft./min. high speed steel*	*Lubricant*	*Cutting Angle and Rake Type*
Iron Cast med.	50–70	Dry or soluble	Radial to 3° Rake or Hook
Malleable	30–45	Dry or soluble or Sulphur base oil	Radial to 3° Rake
Magnesium Alloys	50–80	Paraffin and Lard oil or light oil	10°–20° Hook
Monel	15–25	Sulphur base oil or Paraffin and Lard oil	12°–20° Hook
Nickel Silver	30–50	Sulphur Base oil or Lard oil or light oil	10°–20° Hook
Rubber	60–70	Dry	10°–15° Hook
Steel Cast	20–30	Sulphur base oil	10°–15° Rake
Chrome	15–20	ditto	10°–15° Hook
Mild	40–60	ditto	5° Rake or Hook
Mang.	10–15	ditto	5° Rake or Hook
Molybdenum	15–20	ditto	10°–15° Rake
Nickel	20–30	ditto	10°–15° Hook
Stainless	10–25	Sulphur base oil Tallow and white lead	8°–12° Rake or Hook 8°–12° Rake or Hook
Tool	25–35	Sulphur base oil Tallow and white lead	5°–12° Rake
Tungsten	15–25	Sulphur base oil or Paraffin and Lard oil	10°–15° Rake or Hook
Vanadium	25–35	Sulphur base oil or Paraffin and Lard oil	10°–15° Rake

Other Methods for Internal Threads. These can also be produced by a single point cutting tool in a lathe, in the same manner as external threads, but the process is slow and demands skilled supervision. This method is only used where accuracy requires it, or when the demand would not justify, economically, the provision of special tooling.

Where the demand warrants the initial financial outlay, internal threads in the large diameter range can best be produced by ***multiple-thread milling***, the component being completed in slightly more than one or two revolutions. The method is subject to the same advantages and limitations as when employed to produce external threads. On this large diameter work the milling cutter will have a longer effective life than would a tap, as loss of size due to regrinding does not in the same way debar the milling cutter from producing components to the correct size.

Grinding, for internal threads, is employed only when the highest accuracy is essential, and is reserved in the main for the production of ring gauges. It cannot be considered as a mass production method, being comparatively slow, and $\frac{3}{4}$ in. is approximately the smallest diameter which can thus be threaded.

Inspection and Measurement. On this subject, see the general account in Chapters XIV–XVI. The accuracy of thread forms is usually checked against a graticule in an optical projector with a magnification of 10 to 50 times, or with go and not-go gauges or fine micrometers. For accurate measurement use is made of a diameter-measuring machine (Fig. 14–10) in conjunction with a set of high-precision wires or "lapped-cylinders". These lie inside the grooves on opposite sides of the component, either one each side or (for greater accuracy) one and two respectively, and by using a formula involving a constant for the particular thread form, can be used both to check its shape and to measure its effective diameter.

For Bibliography see end of book.

CHAPTER X

GEARS AND GEAR CUTTING

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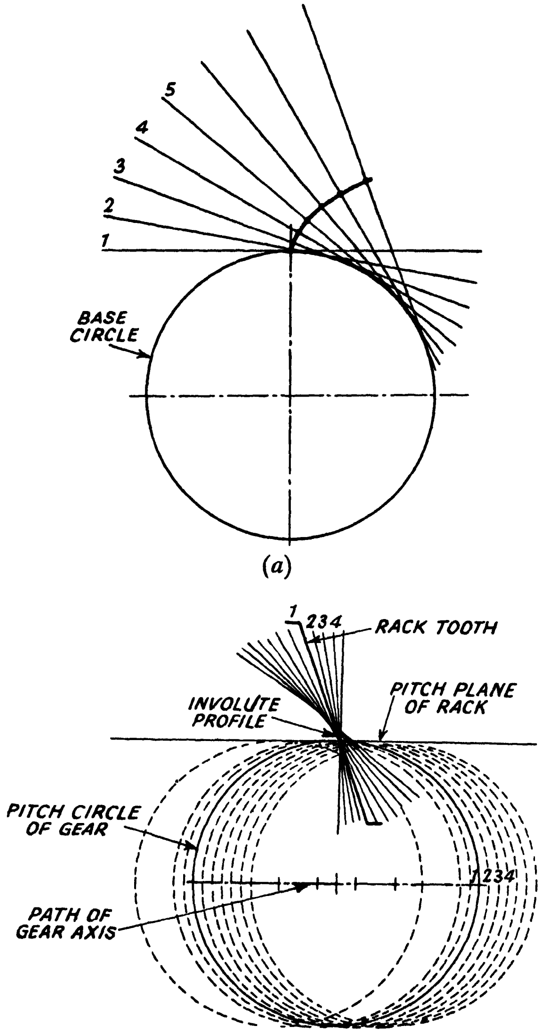
The Involute. Toothed gears are intended to transmit power and motion between shafts. Seldom is the power small enough to be negligible, although this condition obtains in practice with some clockwork and instrument gears; and most industrial applications involve both power and motion. Numerous tooth forms will do this but by far the commonest is one which utilizes part of an involute curve. Such gears are known as *involute gears*. The involute to a circle, as defined by B.S. 2519:1954, is "the curve traced on a plane by a point in a straight line that rolls without slip on the base circle". Although this statement specifies how the curve may be formed, perhaps the simplest way of considering the practical production of an involute gear tooth profile is to regard the circle as the end view of the gear disc which rotates about its axis, while the straight line is the flank of a tooth on a rack moving at the same linear speed as a circle on the disc. Fig. 10.1*a* illustrates the curve traced out according to the definition, where succeeding positions 1, 2, 3 etc. of the rolling straight line are shown. In Fig. 10.1*b*, one flank of a rack tooth is depicted, while the pitch circle of a gear is represented as rolling without slip on the pitch plane of the rack. If the rack tooth is imagined as reciprocating normal to the plane of the paper, the envelope of succeeding impressions is an involute tooth profile. Here also positions of succeeding cuts 1, 2, 3, etc., corresponding to positions 1, 2; 3, etc. of the rolling pitch circle, are indicated, but whereas in Fig. 10.1*a* the straight line generating the involute curve was normal to the curve, in this case the generator is tangential to the involute, that is, it is a tangent at the point specified in the definition.

Definitions. The following generally conform to the terms and notation recommended by B.S. 2519:1954. Fig. 10.2*a* shows a

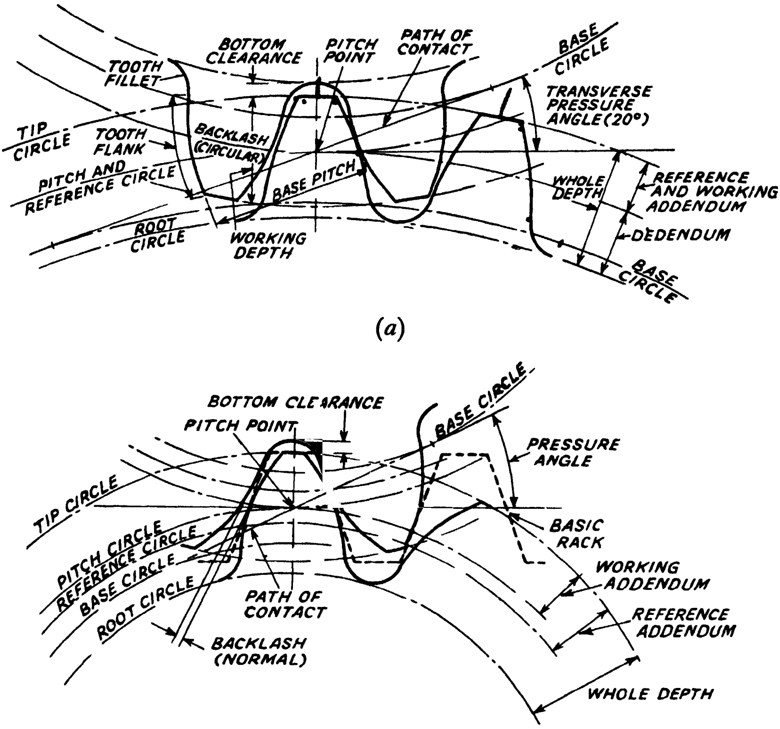


(*a*)

(*b*)

Fig. 10.1

pair of involute spur gears engaging at the designed pressure angle without addendum modification, while in Fig. 10.2*b* the effect of addendum modification may be seen. The gears here are operating at an extended centre distance with larger pressure angle and working pitch diameter; the imaginary basic rack to which both are conjugate



(*a*)

(*b*)

Fig. 10 2

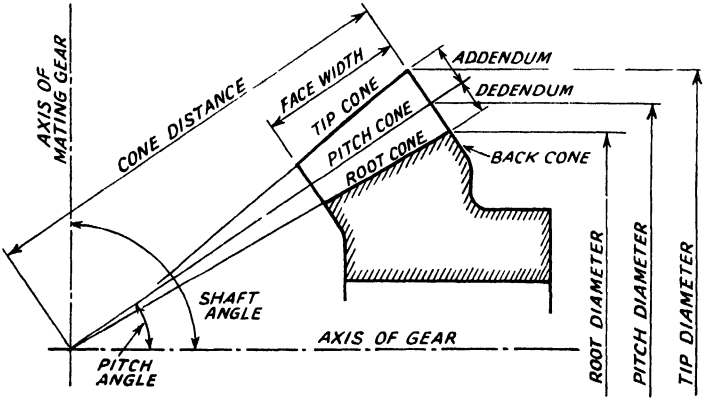


Fig. 10.3

has been added. Where appropriate, the accepted names for the various parts have been included in both diagrams. Fig. 10.3 shows the section of a bevel gear and illustrates the meaning of some of the terms applicable to the type.

Term	*Definition*	*Symbol*
1 Addendum (reference)	The radial distance from the reference cylinder to the tip cylinder	A, a
2 Addenum (working)	The radial distance from the pitch cylinder to the tip cylinder.	A, a
3 Axial pitch	The distance measured along a line parallel to the axis between corresponding successive tooth profiles.	p_a
4 Back cone	The cone on a bevel gear whose generator is perpendicular to the pitch cone generator at the pitch circle.	—
5 Backlash (normal)	The minimum distance between the non-working flanks of a pair of gears when the working flanks are in contact.	z
6 Base circle	The transverse section of the cylinder from which the involutes are derived.	D_o, d_o (diameters)
7 Base helix	The helical path of a point of contact between the generator of an involute helicoid and the base cylinder.	—
8 Basic rack	A rack having teeth of standard profile.	—
9 Bottom clearance	The shortest distance between the tooth crest of one gear and the bottom of the tooth space of the mating gear.	c
10 Cone distance	The length of the pitch cone generator of a bevel gear from the pitch circle to the apex.	C
11 Dedendum	The difference between the whole depth of the tooth and the appropriate addendum.	B, b
12 Diametral pitch	π divided by the spacing in inches of adjacent teeth, spacing measured round reference circle, i.e. diametral pitch = number of teeth per inch of diameter.	P
13 Face width	The total width over the teeth measured parallel to the axis or for bevel gears, along the pitch cone generator.	F, f
14 Gear ratio	The ratio of the greater of the two numbers of teeth to the smaller.	R_g
15 Helix angle	The constant acute angle between a tangent to a helix and the intersecting cylinder generator.	σ

Term	*Definition*	*Symbol*
16 Lead	The lead of the helix of which the tooth trace forms part; the distance which the helix advances along the axis in one revolution.	L
17 Lead angle	The acute angle between a tangent to a helix and a transverse plane.	λ
18 Line of contact	A line defined by all simultaneous points of contact between any two teeth.	—
19 Module	The spacing of adjacent teeth divided by π. Module in inches is the reciprocal of diametral pitch.	m
20 Normal base pitch	The distance between similar flanks of two successive teeth measured along a common normal.	—
21 Normal pitch	The normal pitch of the traces of adjacent corresponding tooth flanks.	p_n
22 Normal pressure angle	In spur, helical and worm gears the acute angle between a radial line passing through any point on a tooth surface and the tangent plane to the tooth surface at that point. In a bevel gear, the acute angle between a normal to the tooth surface at any point on the pitch cone and the tangent plane to the pitch cone at that point.	ψ_n
23 Pitch	The distance between corresponding traces of adjacent teeth measured round the reference circle.	p
24 Pitch angle	The angle between the axis and pitch cone generator of a bevel gear.	γ
25 Pitch circle	The circle of intersection of the pitch cylinder by a transverse plane or for bevel gears, the intersection of the pitch cone and the outer end faces of the teeth.	D,d (diameters)
26 Pitch point	The point of contact of two pitch circles.	—
27 Reference circle	The transverse section of the cylinder on which the normal pressure angle has the specified standard value. When the working transverse pressure angle has the specified standard value the reference and pitch circles coincide; for gears operating at an extended centre distance the working pressure angle is greater than the specified standard value and the pitch circles are greater than the reference circles; a working transverse pressure angle smaller than standard involves pitch circles smaller than the reference circles.	—

Term	*Definition*	*Symbol*
28 Root circle	The transverse section of the root cylinder.	D_r, d_r
29 Tip circle	The transverse section of the tip cylinder.	D_a, d_a
30 Tooth flank	The portion of the tooth surface that lies within the working depth.	—
31 Transverse base pitch	The distance measured in a transverse plane along a common normal to similar profiles of two adjacent teeth.	—
32 Transverse pitch	The distance between corresponding traces of adjacent teeth measured round the reference circle.	p_t
33 Transverse pressure angle	The acute angle between the normal to a tooth profile in a transverse plane at its inter-section with the reference circle and the tangent to the reference circle at that point.	ψ_t

When two symbols are given, the capital refers to the wheel.

It should be noted that gears do not possess pitch circles until they are in mesh with one another.

The gear ratio, $R_g = T/t = n/N$ where T, t are the numbers of teeth in the wheel and pinion respectively and N,n are the speeds in r.p.m. of the wheel and pinion respectively.

Useful Formulae. In order to design a pair of gears with respect to detail dimensions, the following formulae may be used for the types of gear in common use. Suffixes p and w refer to pinion and wheel respectively.

	Spur	*Helical*	*Crossed Helical*
$C =$	$\frac{(t+T)p}{2\pi}$	$\frac{(t+T)p}{2\pi}$	$\frac{p_n}{2\pi}(t \sec \sigma_p + T \sec \sigma_w)$
$C =$	$\frac{(t+T)}{2P}$	$\frac{(t+T)}{2P}$	$\frac{d+D}{2}$
$d =$	$\frac{2C}{(R_g+1)}$	$\frac{2C}{(R_g+1)}$	
$d =$	$\frac{tp}{\pi} = \frac{t}{P}$	$\frac{tp}{\pi} = \frac{t}{P}$	$\frac{p_n}{\pi} t \sec \sigma_p = \frac{t \sec \sigma_p}{P_n}$
$d =$		$\frac{t \sec \sigma}{P_n} = \frac{t p_n \sec \sigma}{\pi}$	
$D =$	$\frac{2R_g C}{(R_g+1)}$	$\frac{2R_g C}{(R_g+1)}$	
$D =$	$\frac{Tp}{\pi} = \frac{T}{P}$	$\frac{Tp}{\pi} = \frac{T}{P}$	$\frac{p_n}{\pi} T \sec \sigma_u = \frac{T \sec \sigma_w}{P_n}$
$D =$		$\frac{T \sec \sigma}{P_n} = \frac{T p_n \sec \sigma}{\pi}$	
$d_o =$	$d \cos \psi$	$d \cos \psi_t$	$d \cos \psi_t$
$D_o =$	$D \cos \psi$	$D \cos \psi_t$	$D \cos \psi_t$

Spur	*Helical*	*Crossed Helical*
$d_a = \frac{t + 2^{*}}{P} = d + 2a$	$d + 2a$	$d + \frac{2\,p_n}{\pi}$
$D_a = \frac{T + 2^{*}}{P} = D + 2A$	$D + 2A$	$D + \frac{2\,p_n}{\pi}$
$a = \frac{1 + k_p}{P} = \frac{(1 + k_p)\,p}{\pi}$	$\frac{(1 + k_p)\cos\sigma}{P}$	$\frac{(1 + k_p)\cos\sigma_p}{P}$
$A = \frac{1 + k_w}{P} = \frac{(1 + k_w)\,p}{\pi}$	$\frac{(1 + k_w)\cos\sigma}{P}$	$\frac{(1 + k_w)\cos\sigma_w}{P}$
$b = \frac{1{\cdot}25 - k_p}{P} = \frac{(1{\cdot}25 - k_p)\,p}{\pi}$	$\frac{(1{\cdot}25 - k_p)\cos\sigma}{P}$	$\frac{(1{\cdot}25 - k_p)\cos\sigma_p}{P}$
$B = \frac{1{\cdot}25 - k_w}{P} = \frac{(1{\cdot}25 - k_w)\,p}{\pi}$	$\frac{(1{\cdot}25 - k_w)\cos\sigma}{P}$	$\frac{(1{\cdot}25 - k_u)\cos\sigma_w}{P}$
	$p_a = p\cot\sigma$	$\begin{cases} p_p \cot\sigma_p \\ p_w \cot\sigma_w \end{cases}$
	$p_n = p\cos\sigma$	$\begin{cases} p_p \cos\sigma_p \\ p_w \cos\sigma_w \end{cases}$
	$L = \pi D \cot\sigma$	$L_p = \pi d \cot\sigma_p$ $= \pi d \tan\lambda_p$
	$L = \pi D \tan\lambda$	$L_w = \pi D \cot\sigma_w$ $= \pi D \tan\lambda_w$
	$\lambda = 90 - \sigma$	
	$\tan\psi_n = \tan\psi \sin\lambda$	
	$\tan\psi_n = \tan\psi \cos\sigma$	
		shaft angle $\Sigma = \sigma_p + \sigma_w$
		$\tan\sigma_p = \frac{R_g/R_d - \cos\Sigma}{\sin\Sigma}$
		$R_d = D/d$

Straight Bevel	*Worm*
$d = \frac{tp}{\pi} = \frac{t}{P}$	$t = \frac{12\sqrt{C} + 7}{R_g}$
$D = \frac{Tp}{\pi} = \frac{T}{P}$	$T = R_g t$
$a = \frac{1 + k_p}{P} = \frac{(1 + k_p)\,p}{\pi}$	$m = \frac{D}{T} = \frac{p}{\pi}$
$A = \frac{1 + k_w}{P} = \frac{(1 + k_w)\,p}{\pi}$	$m_n = m\cos\lambda$
$b = \frac{1{\cdot}25 - k_p}{P} = \frac{(1{\cdot}25 - k_p)\,p}{\pi}$	$C \quad 0{\cdot}5\,(Tm + d)$
$B = \frac{1{\cdot}25 - k_w}{P} = \frac{(1{\cdot}25 - k_w)\,p}{\pi}$	$d \doteqdot 1{\cdot}45\left(\frac{C}{4}\right)^{0{\cdot}7}$
$C = \frac{d}{2\sin\gamma_p} = \frac{D}{2\sin\gamma_w}$	$D = 2C - d$
$= \frac{C}{3}$ *max.*	$d_o = mt\cot\lambda_o$
$d_a = d + 2a\cos\gamma_p$	$a = m$
$D_a = D + 2A\cos\gamma_w$	$b = m\,(2{\cdot}2\cos\lambda - 1)$

* without addendum modification.

Straight Bevel

$$\tan \gamma_p = \frac{\sin \Sigma}{R_g + \cos \Sigma}$$

$$= \frac{1}{R_g} \text{ when } \Sigma = 90°$$

Worm

$$L = \pi \, t \, m$$

$$\tan \lambda = \frac{m \, t}{d}$$

$$\cos \lambda_o = \cos \lambda \cos \psi_n$$

$$A = b - c$$

$$c = 0{\cdot}2 \, m \cos \lambda$$

$$D_a = D + 2A + m$$

$$d_a = d + 2a$$

$$f_w = 2 \sqrt{m\,(\mathrm{d} + m)}$$

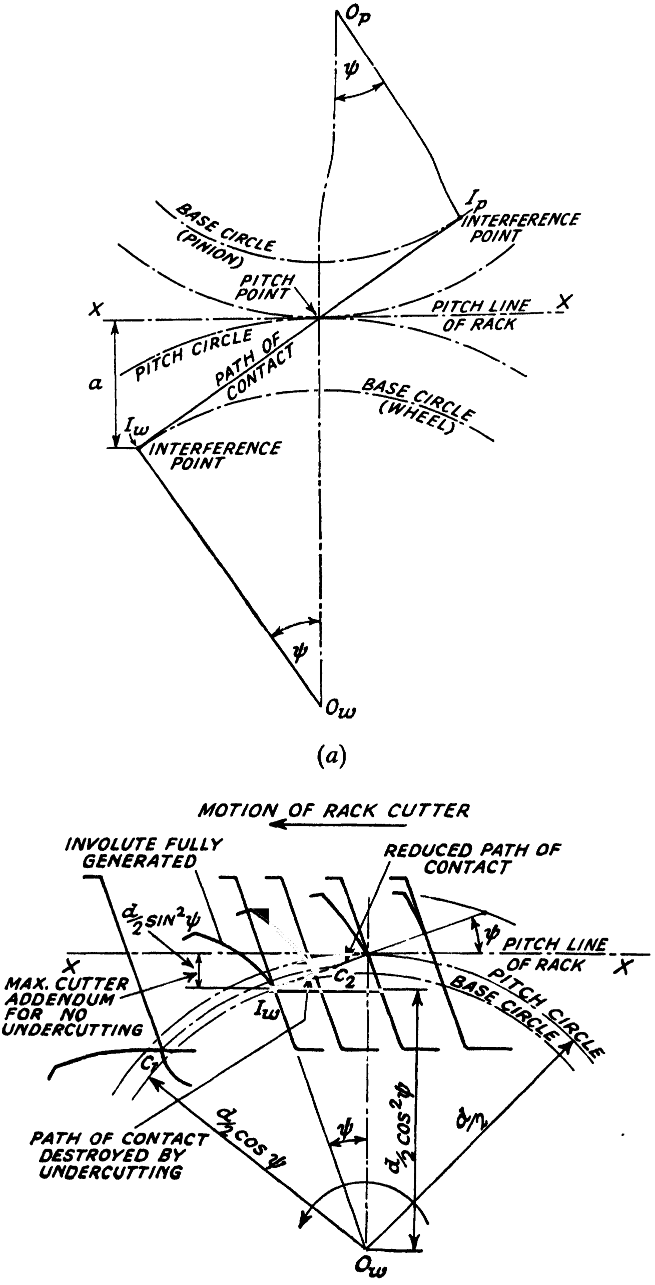
$$f_p = m \sqrt{3\,(2T - 1)}$$

Interference. A true involute profile, by definition, cannot extend below the base circle, and in practice this means that the limits to involute contact along the path of contact are the points of tangency, known as *interference points*, between this line and the base circles. These are shown as I_{P} and I_{W} in Fig. 10.4*a*. Hence, if the addendum of the basic rack cutter exceeds in length the perpendicular distance of an interference point from the pitch line of the rack, undercutting will result. In Fig. 10.4*a* the limiting addendum for complete generation of an involute tooth profile is shown as *a*. Fig. 10.4*b* shows the effect on a gear tooth while being cut, of a rack cutter which has an addendum exceeding the permitted length. During generation a true involute curve is produced until the flank of the cutter reaches I_{W} on the base circle but when cutting is continued the tip of the cutter begins to generate an enlarged tooth fillet which when completed, destroys part of the already finished involute. In many instances in practice the extent of undercutting may not seem to be large but unfortunately it affects an appreciable length of the path of contact. This is illustrated in Fig. 10.4*b* where at point c_1 the cutter has completed generation of the fillet curve; a circle through c_1 cuts the path of contact at c_2 and no contact is possible along $I_w c_2$.

Interference and undercutting of this nature apply to gears with a relatively small number of teeth and it results in a considerable weakening of the teeth in addition to the reduction in the length of the path of contact. To avoid this defect the maximum addendum of the basic rack must be equal to

$$\frac{d}{2} - \frac{d}{2}\cos^2 \psi = \frac{d}{2} \sin^2 \psi$$

If the addendum of the basic rack for unit diametral pitch or module


O_p
ψ
I_p
INTERFERENCE POINT
BASE CIRCLE (PINION)
PITCH POINT
X
PITCH LINE OF RACK
X
PITCH CIRCLE
PATH OF CONTACT
a
BASE CIRCLE (WHEEL)
I_w
INTERFERENCE POINT
ψ
O_w
MOTION OF RACK CUTTER
INVOLUTE FULLY GENERATED
REDUCED PATH OF CONTACT
$\frac{d}{2}\sin^2\psi$
ψ
PITCH LINE OF RACK
X
X
MAX. CUTTER ADDENDUM FOR NO UNDERCUTTING
C_2
I_w
PITCH CIRCLE
BASE CIRCLE
C_1
PATH OF CONTACT DESTROYED BY UNDERCUTTING
$\frac{d}{2}\cos\psi$
ψ
$\frac{d}{2}\cos^2\psi$
$d/2$
O_w

(*a*)

(*b*)

Fig. 10.4

is a and the number of teeth on the wheel below which undercutting will occur is denoted by t_0

$$\text{then } a = \frac{d}{2} \sin^2 \psi = \frac{t_0}{2} \sin^2 \psi$$

$$\text{and } t_0 = \frac{2a}{\sin^2 \psi}$$

For full depth engagement and a pressure angle of 14½° $t_0 = 32$ and for 20° full depth proportions $t_0 = 17$. Three methods of avoiding undercutting are available; reduction of tooth depth, or *stubbing*, increase of pressure angle, and addendum modification, the last being the most widely applicable. Numerous methods have been and still are being promulgated for combining adequate tooth strength with freedom from undercutting.

There are two ways in which addendum modification may be applied. In the first, the mating gears are given equal and opposite addendum modification coefficients so that the addendum of the smaller gear is increased while that of the larger is decreased by the same amount and the centre distance and pressure angle are retained unaltered. This is satisfactory if the elimination of undercutting in the smaller does not result in producing it in the larger, but when both gears are susceptible to the defect it is inapplicable. Then, the second method, of increasing the centre distance, pressure angle and working pitch diameter, is preferable and has much to commend it. Fig. 10.2*b* illustrates a pair of gears engaging at extended centre distance where the reference circle or the pitch circle of generation, is smaller than the pitch circle of engagement.

The method of applying addendum modification specified in B.S. 436:1940 is quite sound and, has proved satisfactory. It is given below applied to spur gears but may be extended to helical, and straight and spiral bevel gears by basing it on the "virtual numbers of teeth". To appreciate the meaning of this expression, suppose a plane section normal to the tooth spirals be taken, then the pitch circles of all these types of gear approximate reasonably closely near the pitch point to those of spur gears of appreciably larger diameters. For bevel gears, such a section is imagined on the back cone. The diameter of an enlarged pitch circle is known as the *virtual pitch diameter* and the number of teeth of the same normal pitch imagined to be cut on a circle of such a diameter is designated the *virtual number of teeth.* Formulae for calculating virtual numbers of teeth appear later in the text.

Referring to Fig. 10.5, if

k = addendum modification coefficient, that is, the displacement of the axis of symmetry of the generating basic rack for unit normal module or unit (*normal pitch*)/π the coefficient being regarded as positive when the displacement is outwards and negative when inwards, then the modified addendum — 0·5 working depth + $k\,p_n/\pi$

Therefore $k = \pi\,(\textit{modified addendum} - 0{\cdot}5\ \textit{working depth})/p_n$

$$\text{Centre distance} = \left(\frac{T + t}{2} + k_p + k_w\right)\frac{\textit{pitch of basic rack}}{\pi}$$

Increase in diameter of modified gears over standard

$$= 2k\,\frac{\textit{pitch of basic rack}}{\pi} = \frac{2k}{\textit{normal diametral pitch}}$$

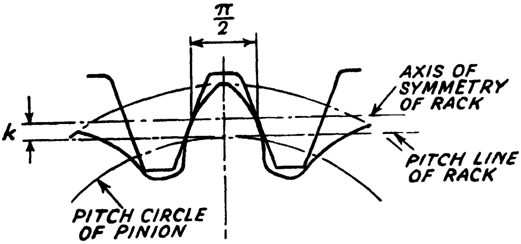


Fig. 10.5

When tooth sum $(T + t)$ is *not less than* 60, the centre distance remains standard, then $k_p = - k_w$ where k_p and k_w are the modification coefficients for the pinion and wheel respectively, that is

$k_p = 0{\cdot}4\,(1 - t/T)$, its minimum value being $= 0{\cdot}02\,(30 - t)$.

When tooth sum is *less than* 60 the centre distance is extended, hence $k_p = 0{\cdot}02\,(30 - t)$ and $k_w = 0{\cdot}02\,(30 - T)$ so that

$$k_p + k_w = 0{\cdot}02\,[60 - (T + t)].$$

To maintain an adequate crest width it is usual to reduce the full depth of gear teeth when the virtual number of teeth is fewer than 17, in which case the addendum increment calculated above should be reduced by

$$0{\cdot}02\,(17 - t_v)\,\frac{\textit{Pitch of basic rack}}{\pi} = 0{\cdot}02\,(17 - t_v)\,\frac{1}{\textit{normal diam. pitch}}$$

When the centre distance is extended the amount by which it is increased is given by $\frac{ep_n}{\pi} = \frac{e}{P_n}$ and the following table gives values of e corresponding to values of $(k_p + k_w)$ for unit diametral pitch

$(k_p + k_w)$	e	$(k_p + k_w)$	e
0.05	0·05	0·4	0·38
0·1	0·1	0·45	0·42
0·15	0·148	0·5	0·465
0·2	0·196	0·55	0·5
0·25	0·242	0·6	0·537
0·3	0·29	0·65	0·57
0·35	0·335	0·7	0·605

The virtual numbers of teeth, t_v and T_v for pinion and wheel respectively, for other types of gear are:

	Helical	*Crossed Helical*	*Straight Bevel*	*Spiral Bevel*
$t_v =$	$t \sec^3 \sigma$	$t \sec^3 \sigma_p$	$t \sec \gamma_p$	$t \sec \gamma_p \sec^3 \sigma$
$T_v =$	$T \sec^3 \sigma$	$T \sec^3 \sigma_w$	$T \sec \gamma_w$	$T \sec \gamma_w \sec^3 \sigma$
virtual ratio	$T_v/t_v = T/t$	T_v/t_v	$T_v/t_v = (T/t)^2$	$T_v/t_v = (T/t)^2$

Another method of effecting addendum modification which has some useful applications, as for instance, when a pinion with a small number of teeth engages with a wheel possessing a satisfactory tooth form, is to design the pinion with overall dimensions suitable for one tooth more than the number actually required, but to cut it with the fewer number of teeth. This is equivalent to giving it modification of 0·5 module or $k_p = 0{\cdot}5 \times$ *pitch of basic rack*$/\pi$. For example, a 10 *t* pinion can be satisfactorily cut in a blank designed for 11 *t* by means of a standard 20° pressure angle cutter. The method increases the backlash but, since in most gears the applied torque does not reverse, this is usually of secondary importance compared with the improvement in strength of the pinion teeth and the better engaging conditions.

Caliper Settings. The usual method of measuring the thickness of individual gear teeth is by means of gear tooth calipers. The length of the chord at the points of intersection of the pitch circle with the tooth flanks is measured for thickness by two anvils and a third anvil, located on the tooth crest, at the same time determines the height setting. This is equal to the sum of the tooth addendum and the height of arc. For this method the tip cylinder diameter must be accurately known and half the desired backlash allowance is subtracted from the nominal thickness of each gear (Fig. 10.6).

Tooth thickness measured round the pitch circle, ignoring backlash, is given by $g = p_n/2 + 2$ (actual modification in in.) $\tan \psi_n$

$= \pi/2\, P_n + 2$ (actual modification in in.) $\tan \psi_n$

The nominal chordal thickness is

$$g_c = g - \frac{g^3}{6}\left[\frac{\pi \cos^3 \sigma}{t\, p_n}\right]^2$$

and the height setting is

$$h = \frac{d_a}{2} - \frac{t\, p_n \sec \sigma}{2\pi} + \frac{g^2}{4}\;\frac{\pi \cos^3 \sigma}{t\, p_n}$$

Backlash is usually necessary in order to permit a pair of gears to run at a fixed centre distance without jamming. It provides accommodation for errors in tooth shape, tooth spiral or pitch, for eccentricity of mounting, axial misalignment, tooth deflection under load; and it permits ingress of lubricant between the contacting surfaces. It is usually measured by fixing one member of a gear pair and rotating the other within the permissible play while a dial indicator is set normal to a tooth profile. This gives the value of the normal backlash which is smaller than the circumferential backlash since if for spur gears, z represents the latter, approximating to the decrease in chordal length, the normal backlash is given by $z \cos \psi$. When applied to helical teeth the normal backlash becomes $z \cos \psi_n \cos \sigma$; usually $\cos \psi_n$ is neglected.

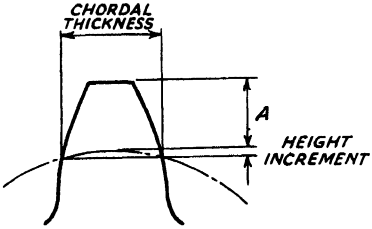


Fig. 10.6

To allow for backlash the permissible tooth thickness is maximum: $= g_c - (0{\cdot}5 z_1 \cos \sigma)$ and minimum: $g_c - (0{\cdot}5 z_2 \cos \sigma)$ where z_1 and z_2 are the permissible amounts of backlash.

If during operation of the gears the transmitted torque remains unidirectional, the amount of backlash is unimportant provided an excessive value does not impair the strength of the teeth.

GEAR DESIGN EXAMPLES

EXAMPLE 1. *Determine the sizes of a pair of* 20° *pressure angle spur gears having a ratio of* 3:1, 4·5 *in. centre distance and* 8 *diametral pitch.*

$$d = \frac{2\,C}{R_g + 1} = \frac{9}{4} = 2{\cdot}25 \text{ in.}$$

$$t = P\,d = 8 \times 2{\cdot}25 = 18$$

$$T = 18 \times 3 = 54$$

$$C = \frac{t + T}{2\,P} = \frac{72}{16} = 4{\cdot}5 \text{ in.}$$

$$D = 2\,C - d = 9 - 2{\cdot}25 = 6{\cdot}75 \text{ in.}$$

$$= \frac{T}{P} = \frac{54}{8} = 6{\cdot}75 \text{ in.}$$

$$D_a = \frac{T + 2}{P} = \frac{56}{8} = 7 \text{ in.}$$

$$d_a = \frac{t + 2}{P} = \frac{20}{8} = 2{\cdot}5 \text{ in.}$$

Pinion		*Wheel*
18	Number of teeth	54
2·25 in.	Pitch circle diameter	6·75 in.
2·5 in.	Tip diameter	7 in.

EXAMPLE 2. *Design a pair of helical gears,* 20° *pressure angle, approximately* 30° *helix angle,* 12 *in. centre distance,* 0·4 *in. normal pitch and about* 5:1 *ratio.*

$$d = \frac{2\,C}{R_g + 1} = \frac{24}{6} = 4 \text{ in.}$$

$$p = \frac{p_n}{\cos\,\sigma} = \frac{0{\cdot}4}{0{\cdot}866} = 0{\cdot}462 \text{ in.}$$

$$t = \frac{\pi\,d}{p} = \frac{\pi \times 4}{0{\cdot}462} = 27{\cdot}2 \text{ say } 27$$

$$T = 5 \times 27 = 135 \text{ say } 137 \text{ to avoid common factors}$$

$$C = \frac{(t + T)\,p}{2\,\pi} = \frac{164 \times 0{\cdot}462}{2\,\pi} = 12{\cdot}05$$

hence gears will be required to run at closed centres but it is preferable to modify the helix angle

$$p = \frac{2\,C\,\pi}{(t + T)} = \frac{24 \times \pi}{164} = 0{\cdot}460$$

and $\cos \sigma = 0{\cdot}8696 \qquad \sigma = 29°35'$

$$d = \frac{27 \times 0{\cdot}46}{\pi} = 3{\cdot}953 \text{ in.}$$

$$D = 2\,C - d = 24 - 3{\cdot}953 = 20{\cdot}047 \text{ in.}$$

Tooth sum $(t + T)$ is not less than 60

$$k_p = -k_w = 0{\cdot}4 \left(1 - \frac{27}{137}\right) = 0{\cdot}321$$

$$a = \frac{0{\cdot}4}{\pi}(1 + 0{\cdot}321) = 0{\cdot}168$$

$$A = \frac{0{\cdot}4}{\pi}(1 - 0{\cdot}321) = 0{\cdot}086$$

$$d_a = d + 2a = 4{\cdot}289 \text{ in.}$$

$$D_a = D + 2A = 20{\cdot}219 \text{ in.}$$

Pinion		*Wheel*
27	Number of teeth	137
3·953 in.	Pitch circle diameter	20·047 in.
4·289 in.	Tip diameter	20·219 in.
29° 35′	Helix angle	29° 35′

EXAMPLE 3. *Calculate the tooth particulars of a pair of* 20° *spur gears with addendum modification, about* 5:1 *ratio,* 10 *in. centres distance and* 7 *diametral pitch.*

$$\text{Pitch diameter of pinion} = \frac{2\,C}{(R_g + 1)} = \frac{20}{6} = 3{\cdot}333 \text{ in.}$$

$$t = Pd = 7 \times 3{\cdot}333 = 23{\cdot}331 \text{ say } 23$$

$$T = 23 \times 5 = 115; \text{ make } T = 117$$

$$C = \frac{t + T}{2\,P} = \frac{140}{14} = 10 \text{ in.}$$

$$R_g = \frac{117}{23} = 5{\cdot}1$$

Tooth sum is not less than 60 since $T + t = 140$

$$k_p = 0{\cdot}4\left(1 - \frac{t}{T}\right) = 0{\cdot}4\left(1 - \frac{23}{117}\right) = 0{\cdot}4(1 - 0{\cdot}197) = 0{\cdot}321 \text{ in.}$$

Minimum value of $k_p = 0{\cdot}02\,(30 - 23) = 0{\cdot}14$

$$k_w = -\,0{\cdot}321 \text{ in.}$$

$$a = \frac{1 + 0{\cdot}321}{7} = 0{\cdot}189 \text{ in.} \qquad A = \frac{1 - 0{\cdot}321}{7} = 0{\cdot}097 \text{ in.}$$

$$b = \frac{1{\cdot}25 - 0{\cdot}321}{7} = 0{\cdot}133 \text{ in.} \qquad B = \frac{1{\cdot}25 + 0{\cdot}321}{7} = 0{\cdot}224 \text{ in.}$$

$$d_a = d + 2a = \frac{t}{P} + 2a = \frac{23}{7} + 0{\cdot}378 = 3{\cdot}286 + 0{\cdot}378 = 3{\cdot}664 \text{ in.}$$

$$D_a = D + 2A = (2C - d) + 2A = 16{\cdot}714 + 0{\cdot}194 = 16{\cdot}908 \text{ in.}$$

$$g_p = \frac{\pi}{2 \times 7} + 2 \times \frac{0{\cdot}321}{7}\tan 20^\circ = 0{\cdot}224 + 0{\cdot}033 = 0{\cdot}257 \text{ in.}$$

$$g_{cp} = 0{\cdot}257 - \frac{0{\cdot}257^3}{6}\left(\frac{7}{23}\right)^2 = 0{\cdot}257 - 0{\cdot}0002 = 0{\cdot}257 \text{ in.}$$

$$h_p = \frac{3.664}{2} - \frac{23}{2 \times 7} + \frac{0{\cdot}257^2}{4} \times \frac{7}{23} = 1{\cdot}832 - 1{\cdot}643 + 0{\cdot}005 = 0{\cdot}194 \text{ in.}$$

$$g_w = p - g_p = 0{\cdot}449 - 0{\cdot}257 = 0{\cdot}192$$

$$g_{cw} = 0{\cdot}192 - \frac{0{\cdot}192^3}{6}\left(\frac{7}{117}\right)^2 = 0{\cdot}192 \text{ in.}$$

$$h_w = \frac{16{\cdot}908}{2} - \frac{117}{2 \times 7} + \frac{0{\cdot}192^2}{4} \times \frac{7}{117} = 8{\cdot}454 - 8{\cdot}357 + 0{\cdot}0006 = 0{\cdot}097 \text{ in.}$$

Pinion		*Wheel*
23	Number of teeth	117
3·286 in.	Pitch circle diameter	16·714 in.
3·664 in.	Tip diameter	16·908 in.
0·322 in.	Total tooth depth	0·321 in.
0·257 in.	Nominal chordal thickness	0·192 in.
0·194 in.	Height setting	0·097 in.

EXAMPLE 4. *Determine the blank diameters of a pair of* 20° *helical gears having* 13/34 *teeth,* 10 *normal diametral pitch,* 20° *helix angle.*

Nominal centre distance, $C = \dfrac{13 + 34}{2 \times 10 \cos 20^\circ} = 2{\cdot}5$ in.

The virtual tooth sum $= (t + T)\sec^3 \sigma = 47 \times 1{\cdot}205 = 56{\cdot}6$

Because this is less than 60

$k_p = 0{\cdot}02\,(30 - t \sec^3 \sigma) = 0{\cdot}02\,(30 - 13 \times 1{\cdot}205) = 0{\cdot}287$ in.
$k_w = 0{\cdot}02\,(30 - T \sec^3 \sigma) = 0{\cdot}02\,(30 - 34 \times 1{\cdot}205) = -\,0{\cdot}219$ in.
$k_p + k_w = 0{\cdot}068$ in.

Hence extension factor e from table $= 0{\cdot}068$ and actual extension

of centres $= \dfrac{e}{10} = 0{\cdot}007$ in.

from which centre distance is 2·507 in.

The virtual number of teeth in the pinion,

$t \sec^3 \sigma = 15{\cdot}67$ which is less than 17 and to maintain adequate crest width the nominal addendum must be reduced by $0{\cdot}02\,(17 - 15{\cdot}67)\,\frac{1}{10} = 0{\cdot}0027$ in.

Nominal $a = \dfrac{1 + k_p}{P_n} = \dfrac{1{\cdot}287}{10} = 0{\cdot}129$ in.

corrected $a = 0{\cdot}129 - 0{\cdot}003 = 0{\cdot}126$ in.

$$A = \frac{1 + k_w}{P_n} = \frac{1 - 0{\cdot}22}{10} = 0{\cdot}078 \text{ in.}$$

$$d = \frac{t \sec \sigma}{P_n} = \frac{13}{10} \times 1{\cdot}06416 = 1{\cdot}383 \text{ in.}$$

$$D = \frac{T \sec \sigma}{P_n} = \frac{34 \times 1{\cdot}06416}{10} = 3{\cdot}618 \text{ in.}$$

$d_a = d + 2a = 1{\cdot}383 + 0{\cdot}252 = 1{\cdot}635$ in.

$D_a = D + 2A = 3{\cdot}618 + 0{\cdot}156 = 3{\cdot}774$ in.

Pinion		*Wheel*
13	Number of teeth	34
1·383 in.	Pitch diameter	3·618 in.
1·635 in.	Tip diameter	3·774 in.

EXAMPLE 5. *Design a pair of crossed helical gears with a centre distance of 4 inches, a pinion diameter of approximately 3 inches and a shaft angle of 45°. The ratio is to be about 2:1 and a cutter of 10 normal diametral pitch is to be used.*

t should be greater than $17 \cos^3 \sigma_p$

and T should be greater than $17 \cos^3 \sigma_w$

$$C = \frac{p_n}{2\pi}(t \sec \sigma_p + T \sec \sigma_w) = \tfrac{1}{2}(d + D)$$

$$R_g = \frac{T}{t}$$

$$\Sigma = \sigma_p + \sigma_w = 45^\circ$$

Usually from these formulae it is necessary to find by trial and error methods a combination of diameters and helix angles to suit the centre distance. In the above example the approximate pinion diameter is specified and values for numbers of teeth and helix angles are required.

$$d = 3;\ D = 5;\ \therefore\ R_d = \frac{D}{d} = 1{\cdot}667$$

$$\tan \sigma_p = \frac{R_g/R_d - \cos \Sigma}{\sin \Sigma} = \frac{2/1{\cdot}667 - 0{\cdot}707}{0{\cdot}707} = 0{\cdot}6973$$

$$\therefore\ \sigma_p = 34^\circ\ 53' \text{ and } \sigma_w = 10^\circ\ 7'$$

$$d = \frac{t \sec \sigma_p}{P_n} \qquad 3 = \frac{1{\cdot}22\,t}{10} \qquad \therefore\ t = 24{\cdot}6 \text{ say } 25$$

then let $T = 49$ to provide a hunting tooth. Now that the numbers of teeth have been determined exact values for the helix angles can be found from the basic equation.

$$4 = \frac{1}{2 + 10}(25 \times \sec \sigma_p + 49 \times \sec \sigma_w)$$

from which $\sigma_p = 33^\circ\ 34'$ and $\sigma_w = 11^\circ\ 26'$

then $d = \dfrac{25 \times 1{\cdot}2}{10} = 3$ in. and $D = \dfrac{49 \times 1{\cdot}02}{10} = 5$ in.

Pinion		*Wheel*
25	Number of teeth	49
3 in.	Pitch circle diameter	5 in.
3·2 in.	Tip diameter	5·2 in.
33° 34′	Helix angle	11° 26′

EXAMPLE 6. *Determine the sizes of a pair of straight bevel gears having* 17/35 *teeth,* 20° *pressure angle and* 12 *mm. module with shaft angle of* 85° *to B.S. proportions.*

12 mm. module = 1·4842 in. pitch

$$d = \frac{17 \times 1{\cdot}4842}{\pi} = 8{\cdot}032 \text{ in.}$$

$$D = \frac{35 \times 1{\cdot}4842}{\pi} = 16{\cdot}535 \text{ in.}$$

$$\text{Pitch angle, } \tan \gamma_p = \frac{\sin \Sigma}{R_g + \cos \Sigma} = \frac{0{\cdot}9962}{2{\cdot}06 + 0{\cdot}0872} = 0{\cdot}464$$

$$\therefore \gamma_p = 24^\circ\, 54' \text{ and } \gamma_w = 60^\circ\, 6'$$

$$C = \frac{d}{2 \sin \gamma_p} = \frac{8{\cdot}032}{2 \times 0{\cdot}4211} = 9{\cdot}537 \text{ in.}$$

$$k_p = 0{\cdot}4 \left(1 - \frac{1}{2{\cdot}06}\right) = 0{\cdot}2058,\ k_w = -\,0{\cdot}2058$$

$$a = \frac{1{\cdot}2058 \times 1{\cdot}4842}{\pi} = 0{\cdot}572 \text{ in.}$$

$$A = \frac{(1 - 0{\cdot}2058) \times 1{\cdot}4842}{\pi} = 0{\cdot}372 \text{ in.}$$

Tooth depth = 1·4842 × 0·7162 = 1·063 in.

$d_a = 8{\cdot}032 + 2 \times 0{\cdot}572 \times 0{\cdot}907 = 9{\cdot}070$ in.

$D_a = 16{\cdot}535 + 2 \times 0{\cdot}372 \times 0{\cdot}4985 = 16{\cdot}906$ in.

$$f = \frac{9{\cdot}537}{3} = 3{\cdot}179 \text{ in.}$$

$$\text{Dedendum angle (pinion), } \beta_p = \tan^{-1}\frac{b}{C} = \tan^{-1}\frac{1{\cdot}063 - 0{\cdot}572}{9{\cdot}537} = 2^\circ\, 57'$$

$$\text{Dedendum angle (wheel), } \beta_w = \tan^{-1}\frac{B}{C} = \tan^{-1}\frac{1{\cdot}063 - 0{\cdot}372}{9{\cdot}537} = 4^\circ\, 9'$$

Root angle (pinion), $\gamma_{rp} = \gamma_p - \beta_p = 24^\circ\, 54' - 2^\circ\, 57' = 21^\circ\, 57'$

Root angle (wheel), $\gamma_{rw} = \gamma_w - \beta_w = 60^\circ\, 6' - 4^\circ\, 9' = 55^\circ\, 57'$

Face angle (pinion) $= 90^\circ - (\Sigma - \gamma_{rw}) = 90^\circ - 85^\circ + 55^\circ\, 57' = 60^\circ\, 57'$

Face angle (wheel) $= 90^\circ - (\Sigma - \gamma_{rp}) = 90^\circ - 85^\circ + 21^\circ\, 57' = 26^\circ\, 57'$

Pinion		*Wheel*
17	Number of teeth	35
8·032 in.	Pitch diameter	16·535 in.
9·070 in.	Tip diameter	16·906 in.
9·537 in.	Cone distance	9·537 in.
24° 54′	Pitch angle	60° 6′
60° 57′	Face angle	26° 57′

EXAMPLE 7. *Design a pair of worm gears to suit a centre distance of* 6 *inches, and a ratio of approximately* 15:1.

Number of threads in worm,

$$t \bumpeq \frac{12\sqrt{C}+7}{R_g}$$

$$\frac{12\sqrt{6}+7}{15} = \frac{12 \times 2{\cdot}45 + 7}{15} = \frac{36{\cdot}4}{15}$$

Make $t = 2$, $R_g = 15$ hence $T = R_g t = 30$

but in order to provide a "hunting tooth" it is usual to make T equal to the next whole number below $R_g t$ i.e. 29

$$d \bumpeq 1{\cdot}45\left(\frac{C}{4}\right)^{0{\cdot}7} \bumpeq 1{\cdot}45 \times 1{\cdot}5^{0{\cdot}7} = 1{\cdot}925 \text{ in.}$$

$$D = 2C - d = 12 - 1{\cdot}925 = 10{\cdot}075 \text{ in.}$$

$$m = \frac{D}{T} = \frac{10{\cdot}075}{29} = 0{\cdot}3474; \quad p = \pi m = 1{\cdot}09 \text{ in.}$$

$$\tan\lambda = \frac{m\,t}{d} = \frac{0{\cdot}3474 \times 2}{1{\cdot}925} = 0{\cdot}3609 \text{ and } \lambda = 19° \; 51'$$

$$L = \pi t m = \pi \times 2 \times 0{\cdot}3474 = 2{\cdot}180 \text{ in.}$$

$$A = b - c = m\,(2{\cdot}2\cos\lambda - 1) - 0{\cdot}2\,m\cos\lambda$$

$$= 0{\cdot}3474\,(2{\cdot}2 \times 0{\cdot}9406 - 1) - 0{\cdot}2 \times 0{\cdot}3474 \times 0{\cdot}9406$$

$$= 0{\cdot}372 - 0{\cdot}065 = 0{\cdot}307 \text{ in.}$$

$$D_a = 10{\cdot}075 + 0{\cdot}614 + 0{\cdot}347 = 11{\cdot}036 \text{ in.}$$

$$d_a = 1{\cdot}925 + 0{\cdot}695 = 2{\cdot}620 \text{ in.}$$

$$f_w = 2\sqrt{0{\cdot}347\,(2{\cdot}272)} = 1{\cdot}8 \text{ in.}$$

$$f_p = 0{\cdot}347\sqrt{3 \times 57} = 4{\cdot}5 \text{ in.}$$

	Worm		*Wheel*
Threads	2	Teeth	29
Pitch diameter	1·925 in.		10·075 in.
Tip diameter	2·620 in.		11·036 in.
Face width	4·5 in.		1·8 in.
Pitch	1·09 in.		
Lead	2·180 in.		
Lead angle	19° 51′		

TYPES OF GEARS

Straight Tooth Spur Gears. The simplest form of gear to connect parallel shafts is that of spur gears in which the tooth flanks are parallel to the shaft axes. When made with standard proportions, spur gears operate with alternately one pair and then two pairs of teeth making contact. For low speeds this does not usually affect their performance but at high speeds even very accurate spur gears tend to be noisy and a normal maximum pitch line speed is about 4000 ft/min. for hobbed and shaved gears and 8000 ft/min. for profile ground gears.

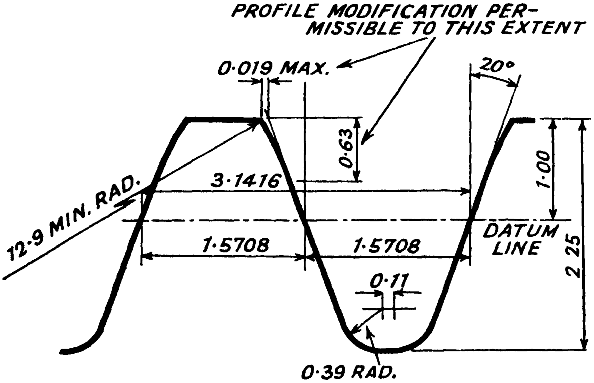


Fig. 10.7

When transmitting torque, all gear teeth deflect and, because the lines of contact lie parallel to the tooth spirals, spur gear teeth deflect along their whole length, so that undesirable hard tip and root contact may result. Tip or root relief, sometimes both together, permit a smoother engagement in such circumstances and reduce shock. B.S. 436:1940 for spur and helical gears gives the permissible value for tip relief, but, since it is also intended to accommodate adjacent pitch errors, the smaller these are the less tip relief is necessary.

Fig. 10.7 shows a basic rack tooth shape illustrating the tip relief specified in B.S. 436:1940 in terms of the addendum for the profile of commercial cut gears.

Helical Gears, like spur gears, connect shafts whose axes are parallel but here the tooth spirals follow a helical path. On every transverse plane they form involutes to a base circle and each tooth surface may be imagined as formed by an involute generator advancing along a helical path. Such gears are known as *involute helicoids.* If a helical gear consists of one helix only it is referred to as a single helical gear. It is usual to make the helix angle as small as necessary to ensure overlap of contact so that the unbalanced axial thrust on each member of a gear pair may be accommodated easily by the bearings. Helix angles are rarely smaller than 7°.

When two helices of opposite hand are cut in the same gear to form the complete face width, the gears are called double-helical gears, and because end thrusts are balanced no thrust bearings are needed. Helix angles for double-helical gears may lie between about 20° and 45° but the standard value is 30°. For correct engagement it is necessary for a gear pair to have the same normal base pitch and for the engaging helices to be of the same helix angle but of opposite hand.

Double helical gears may be cut with continuous teeth or with a gap between them. When produced by hobbing, the gap must permit run-out of the hob when cutting each helix, but when planing or shaping is used a much narrower gap, sufficient to permit the cutter to complete its working stroke with a small amount of overrun, is all that is necessary.

Contact conditions between helical gears are much more favourable to smooth engagement and quietness in operation because all stages of contact between teeth are present simultaneously and continuously. It is usual for not fewer than two pairs of teeth to be in engagement at any instant, and the total length of lines of contact remains nearly constant for all conditions of engagement, thereby permitting the transmission of the optimum tooth loading. In contrast with spur gears, where the lines of contact are parallel to the axes, in helical gears contact lies along straight lines inclined at the base helix angle over the tooth face width. Contact thus begins at the corner of a tooth and traverses axially across the face. End relief in helical gears is, therefore, more desirable than tip relief to ensure smooth engagement although for high speed operation a small amount of tip relief is often specified as a safeguard against scuffing.

Because of their satisfactory engaging characteristics both single- and double-helical gears may be used for very high speeds and the most accurate gears made, irrespective of size, are of this type. The long line of contact gives them a greater load-carrying capacity than spur gears, from considerations of both wear and strength. Fig. 10.8 illustrates a double-helical wheel cut with a gap. Numerous types of double-helical gear are made and the design used depends largely upon its application. Some have their teeth cut in a casting, forging or fabrication whereas others are built up. The type shown is intended for use with a turbine-driven generator and is almost always produced by hobbing. The smaller sizes of wheel up to about 26 in. diameter, are generally made solid and pressed on to the shaft, but larger wheels are made with loose rims shrunk on to a cast iron, cast steel or fabricated centre, while for marine propulsion

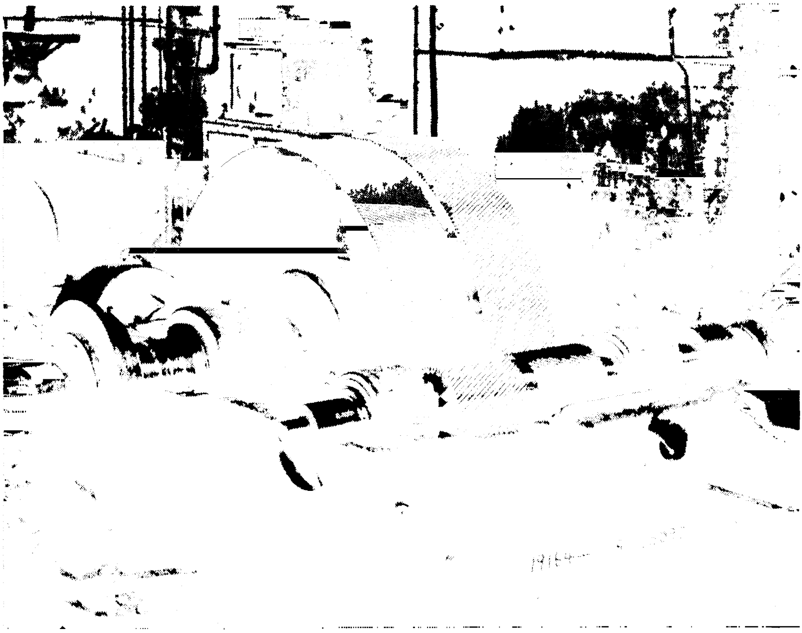


Fig. 10.8

gears a built-up wheel utilizing bolted-on side plates is favoured. Pinions usually, but not invariably, have teeth cut in solid forgings.

Crossed Helical Gears. In crossed helical or skew gears, the base helix angles are not equal although their normal base pitch must be the same. This means that their shaft axes are not parallel but they lie in parallel planes and when viewed along the line of centres make an angle with one another which may be any desired value up to 90°. As a result, crossed helical gears make point contact only and consequently have a low load-carrying capacity. Under load the point becomes a small area and it is necessary for a pair of crossed helical gears to run-in together slowly without scuffing since the worn condition increases the bearing area. Tooth action introduces a sliding component which aids running-in. Each member of a crossed helical gear pair is an involute helicoid and can be cut by any process applied to producing helical gears, but when the helix angles are unequal the numbers of teeth are not in the same ratio as the pitch

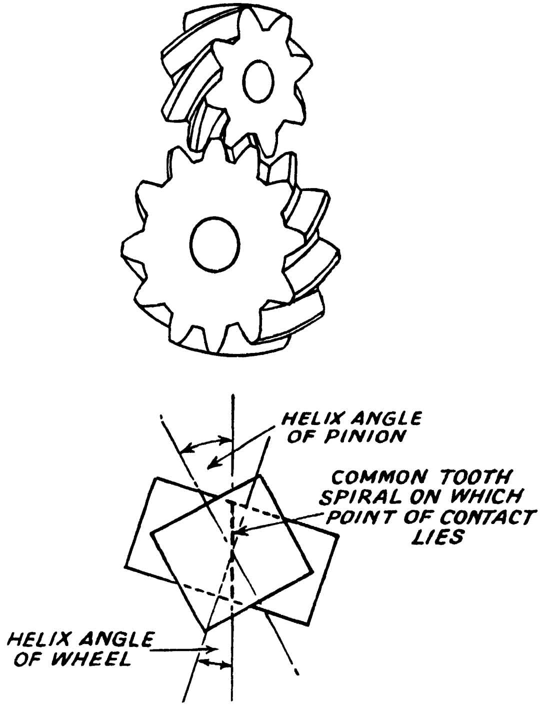


Fig. 10.9

cylinder diameters. A pair is shown in Fig. 10.9; the difference in helix angles in the two gears can be seen.

Bevel Gears, are generally conical in form and connect shafts which intersect in a common plane, most usually but not necessarily, at a right angle. Two types are in common use. When the teeth are radial to the point of intersection of the shafts or apex, the gears are termed *straight bevel gears.* On any plane normal to the pitch-cone generator the tooth profiles form parts of involute curves to a base circle analogous to spur gears and the contact lines between straight bevel teeth lie along the face width of the teeth similar to spur gears. No longitudinal sliding occurs in operation but an end thrust acting away from the apex is developed.

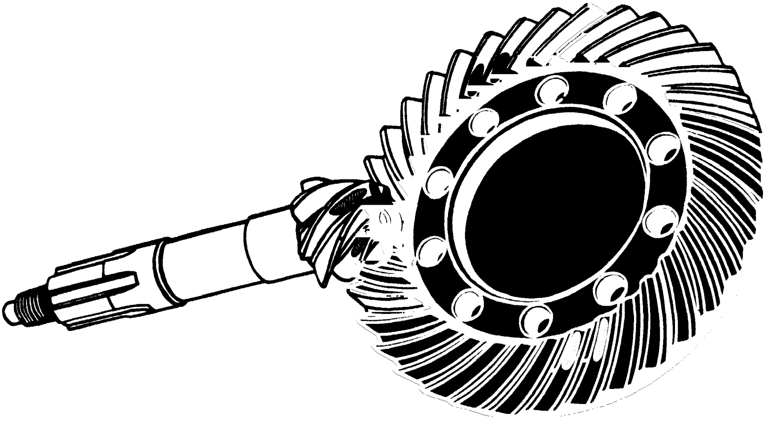


Fig. 10.10

When the cone of one member of a bevel gear pair becomes a flat disc it is known as a *crown wheel* and the point of intersection of the shafts is the centre of the disc, but common usage has also designated the larger of a gear pair of high numerical ratio a crown wheel.

When bevel gears have tooth spirals conforming to circular arcs, or to straight lines offset from the apex, they are known as *spiral bevel gears* and are analogous to cylindrical helical gears. No longitudinal sliding occurs, but the direction of end thrust depends upon the direction of rotation, spiral angle and tooth proportions.

In the production of bevel gears of high numerical ratio the crown wheel is often treated as a rack and the teeth are made straight-sided, particularly when wheels are made in large quantities.

The bottom clearance of bevel gears is usually made the same for all parts of the face width. This means that the tip cone of one gear is parallel to the root cone of its mating gear, and the point of intersection of the tip cone generator with the gear axis does not coincide with the pitch cone apex.

A pair of spiral bevel gears suitable for a road vehicle rear axle may be seen in Fig. 10.10. The inner flange is used for bolting the wheel to the differential cage but in some designs of bevel wheel the flange is omitted and set-screws engaging tapped holes in the back face of the ring fasten it to the cage. On both the wheel and pinion teeth the desirable no-load contact zones are shown as hatched areas. It will be noted that for these gears no-load contact does not extend on either flank beyond half the face width.

Worm Gears are used to connect shafts which lie in parallel planes but do not intersect and, again the angle between the shafts is usually but not necessarily a right angle. They are by far the most versatile of all gears owing to the wide range of ratios permissible for the same centre distance. The worm is a helical gear, generally of large helix angle and when the teeth are of involute form it is an involute helicoid. This is the most usual type. The wormwheel however, is provided with concave teeth and partially envelops the

Fig. 10.11

worm. Worm gears differ from crossed helical gears insofar that they make contact along a line instead of at a point and consequently are capable of carrying heavy loads. Both the worm and wheel of a gear pair produce axial thrust the magnitude of which is dependent upon the transmitted torque and the lead angle.

One important feature of worm gears is the high sliding velocity which is greater than that found with other types of gear, consequently the choice of materials must be given serious consideration since it affects frictional losses. The worm is usually made from case-hardened alloy steel, profile ground on the threads and the wheel is cut in a high-tin bronze ring. Other material combinations are possible for special applications but for road and rail traction and industrial gears required to give optimum service, nothing better than the tin bronze/steel combination has been discovered.

Fig. 10.11 illustrates a pair of involute helicoid worm gears for an industrial worm reduction gear. For the same centre distance the usual range of ratios is from 5:1 to 60:1 but this may be extended at either end.

GEAR CUTTING PROCESSES

Before attempting to cut a gear it is necessary to know its application. Gears should be made to a standard of accuracy adequate to fulfil the required duty, but work is wasted if they are produced to a higher one. Guidance in this direction is provided by the British Standard Specifications for gears which permit a designer to make a suitable choice largely, admittedly, with respect to peripheral speed but the assistance should always be used if possible. For instance, B.S. 436:1940 dealing with spur and helical gears names five classes; A1 for precision ground, A2 for precision cut, B for high-class cut, C for commercial cut and D for large internal gears. The class required and the corresponding accuracy then limits the choice of cutting method to be employed and, often, the standard of accuracy to which the gear-cutting machine itself must be maintained.

Gears are usually produced by cutting tooth-spaces in blanks previously machined to a specified standard of dimensional accuracy, roundness, concentricity and squareness of side faces, utilizing specially designed machines and cutting tools The finished product can often be influenced by the condition of the blank, which certainly affects the ease with which the work can be mounted in the gear cutting machine; hence for high class and precision work, gear blanks are prepared with a great deal of care.

Planing of Spur and Helical Gears. The simplest and probably the most easily understood method of gear-cutting is planing with rack-type cutters. This is a true generating process employing the principle that a straight line generator produces an involute curve when a circle is rolled without slip relative to the generator, as explained earlier. In practice, the gear blank is mounted in the planing machine with its axis either horizontal or vertical, depending upon the type of machine used, and it is given a rotary motion about its axis while the cutter advances in the direction of its length at the same speed as that of the pitch circle of the gear to be cut.

The relative motions of the work and cutter are positively ensured by change gears and a very light marking cut is usually made on the blank to check the accuracy of the calculations, before sinking in the first roughing cut. Cutting is then effected for spur gears by imparting to the rack cutter a reciprocating motion across the face width of the blank in a plane parallel to the axis of the work. At the end of each working stroke the cutter is moved back a short distance, out of contact with the work, to prevent rubbing during the return stroke. An advance of just over one pitch is made by the cutter before rotation of the blank is arrested, the cutter then being returned to its original position and the process repeated. Depth of tooth is obtained by sinking the cutter deeper into the blank in successive revolutions, the number of roughing cuts depending upon the pitch of the gear. A final light cut is always made for finishing the tooth flanks and, particularly for large gears, this is often carried out with freshly-sharpened cutters. To lubricate the cutting edges and carry away heat, a copious stream of cutting oil is directed on to the cutter and work in the zone of engagement. This is supplied as a wide curtain across the face width from a distributor placed above the workpiece.

Helical gears are cut by reciprocating the cutter in a path inclined to the axis of the work corresponding to the tooth spiral required and since the standard helix angle is 30°, machines for producing helical gears are provided with 30° cutter guides.

Few single helical gears are planed with a 30° helix angle and accordingly most of the helical-gear planing machines are made for producing double helicals. Such a machine, shown cutting a double-helical pinion with helical rack-type cutters, may be seen in Fig. 10.12. The work is supported at each end to ensure its maximum rigidity. This machine is capable of cutting gears ranging in diameter from 10 in. to 15 ft. and face widths up to 20 in. The cutters can be seen held in the cutter boxes, one of which can be discerned behind and below the work, while a pair of freshly-sharpened cutters may be observed on the side of the machine bed. The gib strips, inclined at 30°, for adjusting the tool slides, indicate the direction of travel of the cutters. Double-helical gears necessitate the use of two helical rack-cutters reciprocating alternately on each helix, the cutters in turn travelling a distance slightly more than the face width of the helix. Many blanks for double-helical gears are provided with a turned groove into which the cutters project at the ends of their working strokes; the pinion illustrated is of this type. For continuous teeth the formation of a flash is prevented by providing an overrun of the working stroke for each cutter of about 0·010 inch.

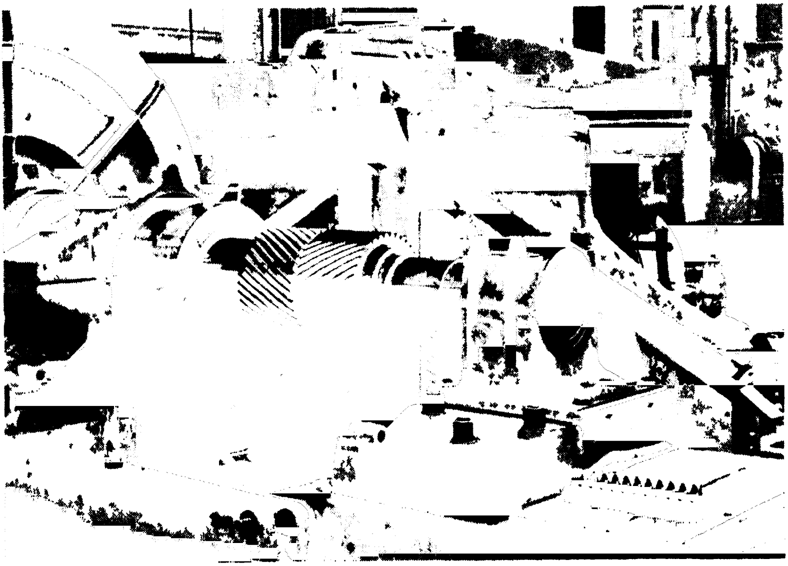


Fig. 10.12

Cutters are usually made from high-speed steel, ground all over to a high degree of accuracy and relieved to provide top and side rake. Spur gears are cut with spur racks while helical gears utilize helical racks, in which the trailing edge of the cutter is "nicked" by a grinding wheel to provide a suitable side rake. Sharpening is effected by grinding back the faces of the teeth, and cutters retain their original profiles throughout their life because of the uniform relief provided.

Form Milling is a method in which the profile of the cutter conforms to the tooth space required. The cutter itself may be in the form either of an end mill or a circular disc. End milling is commonly used in the manufacture of heavy rolling-mill pinions and similar helical gears of large pitch, while the chief function of the circular cutter is heavy stock removal in large spur gears of large pitch, or for gears destined to be finished by a more accurate method such as profile grinding. No better process has yet been found for rough cutting worms. For this type of gear cutting the accuracy of the work produced depends upon the accuracy of the cutter profiles and on the indexing mechanism since each space is finished individually and succeeding spaces are cut by indexing round the gear blank.

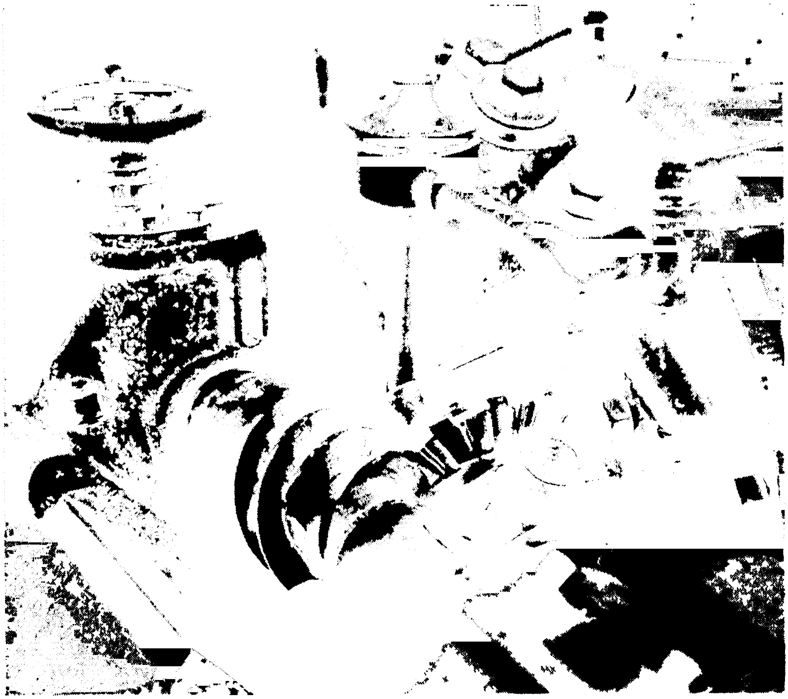


Fig. 10.13

For worms the cutter is engaged with the blank to the full depth of the space and is inclined to the axis of the blank at the designed lead angle. The work traverses a helical path and at the end of a pass the cutter head is withdrawn from mesh, the work returns to its starting point, is indexed to the next thread and the process repeated until the worm is completed.

Each pitch requires a cutter to suit the size of thread being formed and worm-milling cutter profiles take into account potential interference with the thread shape, which might otherwise be damaged after the cutter has passed the zone of maximum cutting depth.

A worm in the process of thread milling is shown in Fig. 10.13. The work piece illustrated is a multi-start worm and the thread profiles are cut with sufficient allowance on thickness to permit the threads to be finished by grinding 0·005/0·010 in. from each flank after case-hardening.

Gear Shaping. Since an involute gear will roll with any other involute gear of the same normal base pitch the principle has been utilized in the gear-shaper method of gear manufacture. In this the cutter is made in the form of a pinion provided with relieved cutting edges, and both cutter and work are given rotary motions about their respective axes to simulate the conditions obtaining had both members been complete gears rolling together at the correct centre distance. This is achieved by gearing the cutter to the work in the same ratio as the numbers of teeth in the cutter and the finished work. Cutting is effected by imparting axial reciprocating motion to the cutter coincident with its rolling action, the length of stroke of the ram being slightly more than the face width of the blank.

For spur gears the reciprocating motion is made parallel to the work axis, but for single-helical gears the direction of the cutting stroke follows a helical path and the cutter itself is provided with helical teeth. The cutter is fed radially into the blank in succeeding cuts until full depth is attained and the teeth have the same pressure angle as that of the cutter on the pitch circle of generation.

The provision of two opposed cutter guides, with their axes horizontal, along which one cutter advances in a working stroke in turn while the other is being withdrawn, enables double-helical gears to be cut. To prevent the cutter rubbing during its withdrawal, the cutter ram is rocked slightly away from the work as soon as the working stroke is completed. As with rack planing of double-helical gears the blanks are often provided with a turned groove to separate the helices, but continuous teeth can be produced without a central flash by overrunning the helix width by about 0·010 in.

The double-helical gear depicted in Fig. 10.14 is of the continuous-tooth type, being cut without gap. The two cutters of opposite hand and a helical guide are clearly seen behind the work piece.

Gear-shaper cutters are relieved on the tips and flanks of the teeth so that as the cutter face is ground back during re-sharpening the front profiles of the teeth remain parts of involute curves to

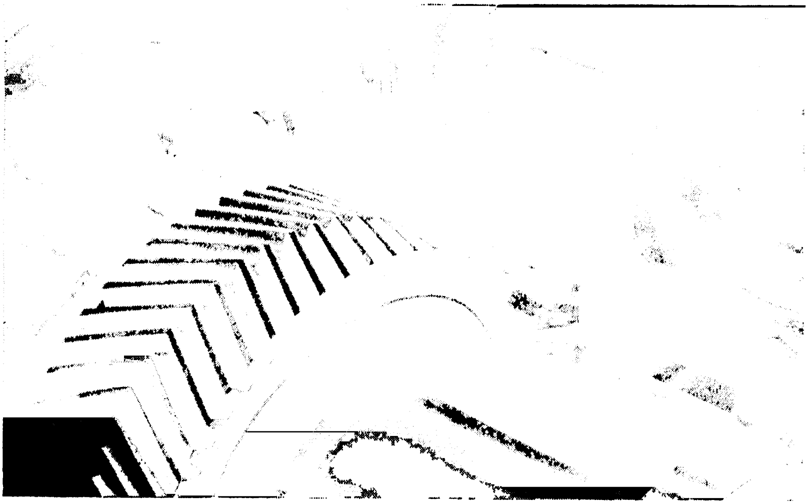


Fig. 10.14

the same base cylinder and identical gears may be produced by the same cutter throughout its life.

Hobbing is extensively used as a means for producing many types of gear and differs considerably from end milling, planing, shaping and spiral bevel-gear milling but bears some resemblance to rotary milling. It is, however, essentially a generating method of gear production since the hob takes the form of a helical gear when cutting spur and helical gears, and meshes with the gear being cut in the same manner as a pair of crossed helical gears would mesh together.

For the purpose of cutting the blank the hob is carried on a spindle, the axis of which is oriented at an angle to suit the angle of the hob spiral and the spiral of the work-piece tooth. Both hob and blank are then rotated about their respective axes at speeds corresponding to the numbers of threads in the hob and the teeth in the work-piece.

Cutting is effected by feeding the hob radially into the blank and traversing it slowly across the face parallel to the axis of the work. Because the hob and work together form a crossed helical-gear pair they make point contact, and generation of an involute tooth proceeds as the envelope of a series of such contact points. How closely this envelope of contact points approximates to a true involute curve depends upon the number of teeth or gashes in the hob and the distance the hob traverses across the face of the work for each revolution of the work.

The hob usually consists of a single thread with numerous gashes across the face, depending upon the diameter of the tool. These may be either parallel to the axis or normal to the thread spiral and the centre line of the tooth thus formed is generally radial. To permit cutting action, each tooth is relieved in a hob-relief grinding machine in such a manner that as the teeth are ground back during any subsequent re-sharpening process they retain their original shape and size although the outside diameter is reduced. This permits a hob to be used after numerous re-sharpenings until the teeth become too thin to support the cutting loads. In service, wear takes place on the tips of those teeth doing most of the work and is manifested by a worn land which must be removed during re-sharpening. It is normally unwise to permit more than 0·020 in. land to form.

Hobs may be made either integral with the hob spindle or bored for mounting on as short and stiff a spindle as possible, and the degree of accuracy specified by British Standards, for turbine gear hobs particularly, (*see* B.S. 2062:1953) is very high. Further, for a satisfactory standard of the finished work the hob must be set in the machine to run truly about its axis within a small tolerance not exceeding 0·0003 in. and the closer it is to perfection the better the work.

Although the majority of spur and helical gear hobs are made with a single start, for some applications multi-start hobs may be used. The use of two or three threads implies, since wear will be distributed over more hob teeth than with the single thread, that more work will be produced. Some loss of accuracy may however ensue from the use of a multi-start hob owing to the difficulty of making both types with equal accuracy and, moreover, for a specified cutting speed the hobbing-machine table must rotate twice or three times as fast as when a single start hob of the same diameter is used. In consequence the machine must be capable of accommodating the higher speed. In practice, the full advantage of the increased cutting speed is not usually attained since, to obtain equal life between grinds from both single- and two-start hobs, the feed per revolution of the work is usually smaller with the two-start hobs and the ultimate benefit is less than two to one. Not every gear is suitable for two-start hobbing. Size of gear, pitch, depth of cut permissible and other factors must be considered, but where it is practicable, it may also be economical, particularly for rough cutting gears destined to be finished by another method.

In Fig. 10.15 is shown a spur gear in the process of being hobbed by a single-start hob in which the relieved individual cutting teeth can be seen engaging with the tooth spaces they are producing in the gear blank.

Fig. 10.15

When hobbing helical gears the hob thread is oriented to suit the desired helix angle and it is usual to employ a right-hand hob for a right-hand spiral and a left-hand hob for a left-hand spiral. This is not a hard and fast rule since, theoretically, either hand of hob may be used for either hand of spiral, but adherence to it ensures that the cutting load operates in a direction opposite to the direction of rotation of the table and the effect of any backlash in the table drive is nullified. As in spur gears, hob and work are given rotary motions about their respective axes corresponding to the numbers of threads in the hob and teeth in the work, but in addition to the above motions the hob is given a further motion to compensate for the advancement or retardation which it would have undergone had it been meshing with a stationary helical gear.

When setting the hob, provided it has sufficient teeth to generate the work-tooth involutes reasonably closely, no advantage is gained by locating a particular hob tooth to a tooth space in the work, except when hobbing fewer than 11 teeth. It is usual, however, so to locate the hob relative to the work that maximum wear occurs near one end; it may then be moved axially to bring an unused zone of the hob teeth into use thus increasing the life of the hob between regrinds.

Worm gears are hobbed by methods similar to those used for the generation of spur and helical gears but one important difference is the omission of the traversing motion across the face of the work. The hob itself is similar in form to the worm but the threads are gashed and relieved to make cutting edges so that the worm-wheel teeth, when generated, partially envelop the worm. Three methods of cutting worm-wheels are available in the hobbing process In one the hob is fed radially into the work to the correct centre distance for the gear pair; in the second, the hob, set at full cutting depth, is fed tangentially past the work while in the third, it is fed radially to depth and combined with a short tangential feed to improve the tooth surfaces. Cutter and work are given rotary motions about their respective axes with their relative speeds corresponding to the numbers of threads in the hob and teeth in the wheel, while at the same time, and resembling the motions of the hob and work when cutting helical gears, the hob is given a further rotary motion to compensate for the movement which it would have made had it been engaging with a stationary wheel.

An industrial worm-wheel consisting of a bronze rim on a cast-iron centre appears in Fig. 10.16 mounted on a worm-wheel generator. The hob is one often used for "roughing" the teeth. They are finished by means of a serrated hob, in which the flanks of a worm are not gashed but provided with closely-spaced serrations cut from tip to root in a transverse plane; when the worm has been hardened and profile ground these form cutting edges.

There has been a tendency to increase cutting speeds for hobbing small- and medium-sized spur and helical gears up to three or more times that formerly considered practicable, and speeds of 350 ft./min. with a feed rate of 0·080 in. are commonly used in robust rigid hobbing machines specially built for the purpose. For such

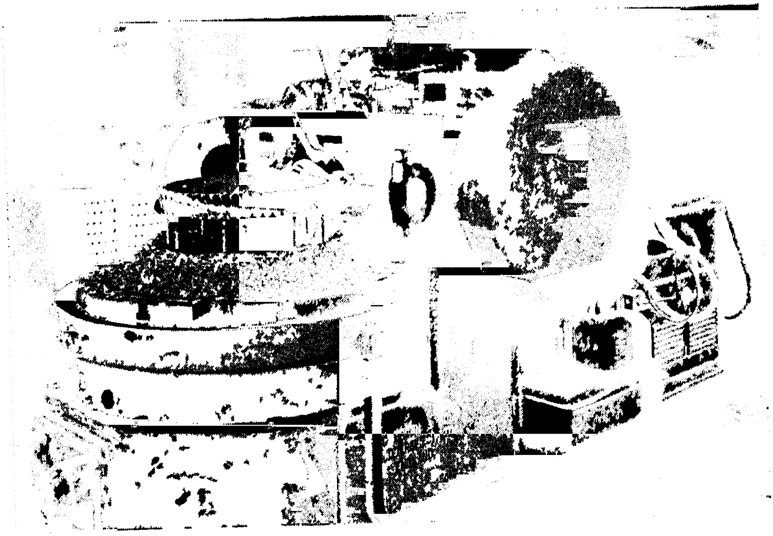


Fig. 10 16

Fig. 10.17

speeds the work material is in the soft or normalized condition and the cut gears have their tooth flanks finished by a subsequent operation such as shaving or profile grinding. Many automotive gearbox gears are now cut by this method and it is usual to design them so that they may be cut in pairs with abutting faces.

In the hobbing machine in Fig. 10.17, numerous changes from the orthodox have been made in addition to its inherent rigidity. For instance, the direction of the hob traverse is inclined to the horizontal to suit the helix angle of the work-tooth spirals, while the hob slide is oriented to the worm angle of the hob. It is usual to set the hob to full tooth depth on the work and to traverse it across the face of the work using climb cutting.

As a contrast in cutting speeds, when cutting large turbine reduction gears on a hobbing machine conforming to the exacting requirements of B.S. 1498:1954 it is common practice to use low rates of cutting speed and feed with the machine housed in a temperature-controlled room.

Milling of Spiral Bevel Gears. More than one type of spiral bevel-gear is in use today, but in most of them the tooth spirals

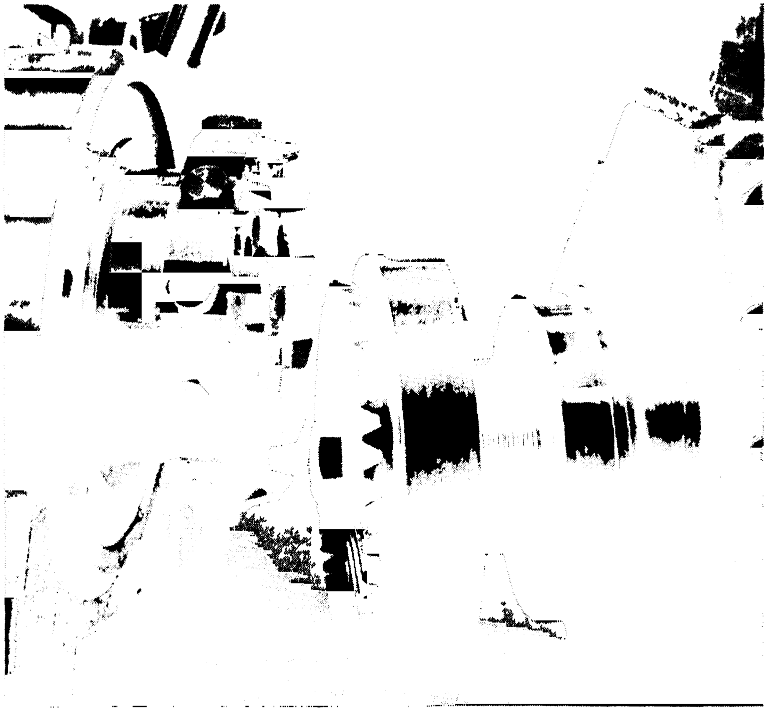


Fig. 10.18

conform to circular arcs, and in generating such gears the milling cutter employed sweeps out the basic crown wheel with which both the cutter and the work are imagined to be engaging. The cutting tools are carried in a circular milling head and are positioned near the periphery with their cutting edges parallel to the axis of rotation.

Both the cutting tool and the shape of the tooth spirals are easily discernible in the detail of a spiral bevel-gear generator depicted in Fig. 10.18.

In cases where the bevel wheel of a gear pair is cut without generation, i.e. the teeth are straight-sided, the whole of the generated shape is applied to the pinion. This is effected during cutting by giving the pinion a rolling motion about its axis similar to that which it would undergo when engaging with the basic crown wheel. Because during operation it is required to keep heavy tooth contact clear of the tip and root in bevel gears, the rolling motion for the pinion during generation is carried slightly beyond the minimum necessary for the complete generation of the theoretical involute profile or, in other words, the pinions are provided with tip and root relief.

Since the most numerous of the spiral bevel-gears manufactured are case-hardened after cutting, the extent of the consequent distortion must be anticipated during cutting so that the desired contact conditions are obtained after hardening.

GEAR FINISHING PROCESSES

Although many gears are entirely satisfactory for their intended application "as cut", either hobbed, planed or shaped, for others an additional finishing process is either necessary or desirable. All the mechanical finishing processes in common use are intended to emend tooth shape by making the flanks conform more nearly to the true or modified involute desired and to improve surface finish and tooth spacing.

Gear Shaving is the newest method of gear finishing, although it was probably first used more than twenty-five years ago to improve contact and finish on worm-wheel teeth. When used for worm-wheels a serrated hob, usually produced with thin threads, is rotated about its axis in mesh with a worm-wheel in which the teeth have already been cut but have not quite the desired shape or surface finish. The wheel is rotatable about its axis, which is perpendicular or nearly so to the axis of the hob, and load is applied by a brake on the machine table carrying the worm-wheel. Since the closely-spaced serrations have no relief, removal of metal is effected by taking fine shavings from those parts of the tooth surface which project above the desired surface. Shaving becomes more difficult as the wheel approaches closer to ideal conjugate action with the hob, and further metal removal can be effected only by slightly deforming the surface of the work, by imposing brake resistance on it.

This principle was later applied to spur and helical gears by using a cutter harder than the work, one in the form of a conjugate gear which meshes with it in such a way that when rotated together relative sliding between cutter and work teeth obtains. Here the cutter is essentially itself a spur or helical gear of the same normal base pitch as the work. The teeth are serrated normal to the tooth profiles and in operation the cutter and work are meshed together as helical gears with the planes of their respective axes crossing. In action, one member of the pair is driven and makes the other rotate, the non-parallelism of the axes causing sliding action between the teeth. The value of the crossed axis angle controls the finish produced to some extent since the smaller the angle the finer the finish. Angles range between 8° and 45°, with 15° generally found most satisfactory.

Under the shaving load which may be applied either tangentially by means of a brake on one member, or radially by crowding the cutter hard into mesh with the work, the theoretical point contact between cutter and work becomes an elliptical area owing to local deformation of the work tooth material. As the cutter and gear rotate together in mesh relative sliding takes place at every point of contact and the serrated cutting edges remove fine shavings from the work. In the same way as worm-wheel teeth, when cut, always deviate slightly from the ideal form, so spur and helical gear teeth may depart sufficiently from the true geometrical shape to make shaving a practical finishing process.

Shaving improves gear tooth finish where the cutting process has not provided the required standard e.g. that with high speed hobbing; but the cut gear must have small errors only in pitch, profile and concentricity. The process is ideal for automotive gearbox gears after hobbing and before hardening.

Shaving can be applied to spur and helical gears over a wide range of sizes. Fig. 10.19, where the cutter is engaging with a small spur pinion, shows the form of shaving cutter teeth and the crossed axes. The process has latterly been applied to much larger gears e.g. those for high-precision turbine work, where it serves the further useful purpose of improving contact; it is normal practice for many turbine gear-makers to shave both wheel and pinion. Usually the wheel is finished first; two or three passes may be needed to clean up the full face width. Pinion and wheel are then rotated together with a marking medium at their working-centre distance, either in the gear case or in a meshing frame, and from the result contact distribution across the face width may be observed. Any hard patches are eased by selective shaving on the pinion, that is, by causing the shaving cutter to make additional passes over the affected length of face after the teeth have been cleaned up.

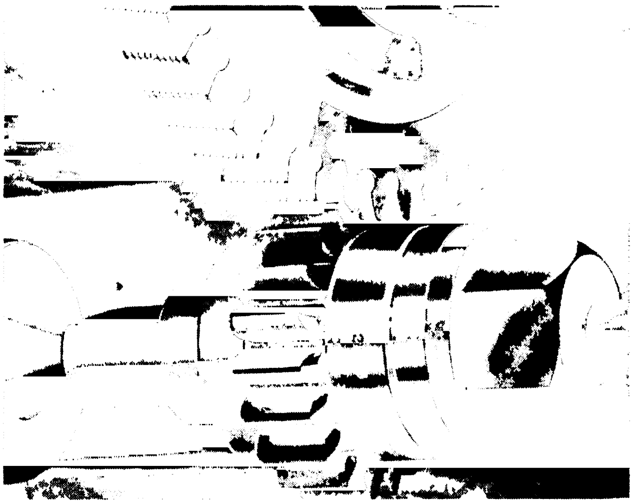


Fig. 10.19

Shaving is also being used for finishing internal gears forming the annuli of epicyclic gear trains. These are almost invariably made from heat-treated steel and may have a U.T.S. between 55 and 75 tons/in.^{2} The teeth are usually cut by one of the gear-shaping methods; shaving tends materially to improve finish, and to reduce tooth spacing and profile errors with a resulting reduction in operating noise.

Gear Grinding as a profile-finishing process for some types of case-hardened (e.g. heavy-vehicle) gears is becoming a declining practice, because the cheaper shaving operation is entirely satisfactory. But when the high accuracy associated with profile grinding is required, it is still extensively used. By the grinding process, teeth may be finished either by generation or by forming. In the first method the work is made to roll in contact with a flat-faced rotating grinding wheel simulating one flank of the basic rack, and each flank of the work tooth is finished separately. In the second, the grinding wheel is formed to the space between two adjacent teeth and both flanks are finished together. The second method tends to.be rather quicker, but both give equally accurate results, and which of the methods is used often depends upon the availability of a grinding machine.

Fig. 10.20

For worms both methods are used, although in recent years the form-grinding process has been more extensively applied. A worm-grinder using the "formed wheel" method is illustrated in Fig. 10.20. The profile of the grinding wheel is trimmed to the correct shape by means of diamonds controlled by suitably-shaped cams, mounted on the grinding head, and when grinding British Standard involute helicoidal worms it produces a truly involute thread profile on the transverse section. Each thread space is finished separately by the worm traversing a helical path axially past the grinding wheel which is fed into the desired depth before grinding starts. At the end of each working stroke the work is drawn out of engagement with the wheel and returned to its starting point where, after it has been indexed round to the next thread space, the grinding wheel again engages to the required depth and the process is repeated.

Coincident with the decline in grinding as applied to smaller gears, its employment as a finishing process for larger gears has increased, and the introduction of case-hardening to turbine gears has made profile grinding a necessity. Machines capable of dealing with large gears are necessarily large themselves but they are capable of finishing the work to as high a standard of accuracy as their smaller fore-runners. In common with hobbing and shaving machines used for manufacturing large gears they are appreciably affected by temperature changes, and to obtain the desired standard of accuracy, must be housed in a temperature controlled room. These machines permit tip and root relief, helix correction, or barrelling, when needed, to be applied simultaneously and the effect of the profile and helix correction is finally confirmed by trial and error as when selective shaving is used to obtain the same result with soft gears. A setting frame is utilized in which the axes of the gear pair are set parallel, or inclined to one another by the required deflection allowance, and the tooth spirals are deemed to be correctly ground when contact is evenly distributed over the face width.

Gear Lapping is a third extensively-used process of gear finishing, in which a pair of gears is run together with an abrasive suspended in a carrier which may be either a fluid or a grease possessing some lubricating properties. Possibly the principal application is that made in the finishing of spiral-bevel and hypoid gears in which the cut pair is run together in a special machine made to simulate conditions obtaining in service, the abrasive being suspended in a lapping oil and pumped to the zone of contact. During cutting, such gears are provided with an allowance on the tooth spirals to compensate for deflection under load, and this is particularly applicable to vehicle driving gears. All such gears and most industrial bevel gears are case-hardened, therefore the cutting operation takes into account the consequent distortion and lapping becomes essentially a polishing process. Even the largest gears should be lapped within about 15 minutes and smaller ones can be finished in fewer than five minutes; prolonged lapping may damage the profiles and only exceptionally is it used for profile or pitch correction.

The extent of the contact zone depends upon the loading the gears are expected to sustain. Because gears, bearings and housing all deflect under load, allowance is made in cutting and lapping so that when the gears are loaded to capacity the "high shine" does not extend to the edge of the heel end. This means that under no-load conditions, contact covers an area (materially affected by the mounting and hence rigidity) between about 70 per cent of the face width for the stiffest industrial and axle units, to about one half this for the most flexible; the final amount is determined whenever possible by performance in service. The commonest disposition of the no-load contact zone is for it to finish at about 50 to 60 per cent of the total face width beginning about 5 to 10 per cent clear of the toe end.

Contact must also be clear of the tip and root; this is obtained by rolling the pinion slightly past the true involute position during generation and lapping. Hard tip and root contact is apt to cause proneness to scuffing.

Automotive gearbox gears finished before case-hardening by shaving are usually, although not always, finally lapped. It is part of the gear designer's art so to proportion tooth depth, web, rim and hub thicknesses that a gearbox gear naturally tends to maintain its shape when heated and quenched and is resistant to rim collapse. Hence, provided the gears are cut and shaved within the prescribed limits of accuracy, the final product is often satisfactory without recourse to final lapping. Small pitch and shape errors can be improved, however, by running the hardened gears in a special lapping machine in engagement with cast-iron gears of the same normal base pitch supplied with an abrasive suspended in lapping oil and pumped to the zone of engagement.

Other Finishing Processes often take the form of refinements to the above basic methods. For instance, *super-finishing* applied to worm threads is a type of very fine grinding and has superseded the lapping and buffing formerly used to impart a smooth finish. Fine *shot blasting* provides a finish resembling that produced by lapping, although it has other functions, such as removing slight burrs, removing or reducing stress raisers in tooth fillets and, sometimes providing slight tip and root relief to teeth. Similar results may be obtained by electrolytic methods.

Shot peening is in rather a different category, for it is applied with the intention of imparting to a gear tooth a greater resistance to fracture. By increasing the natural compressive surface stress in case-hardened gearbox gears it is capable of increasing resistance to tooth breakage by about 10 to 15 per cent, but careful control is most important since it is possible to originate a stress-raising crack which may result in premature failure.

Phosphate coating of gear teeth is a chemical process which attacks the treated ferrous surface and leaves a deposit on it of about 0·0005 in. thickness. It prevents or retards scuffing, particularly in hypoid gears, apparently by permitting the engaging tooth surfaces to bed in more readily under the prevailing boundary lubrication conditions.

For Bibliography see end of book.

CHAPTER XI

ELECTRIC MACHINING OF METALS

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PRESENT practical applications of electricity for direct machining of metals can be divided into four groups: (1) Arc machining; (2) Spark machining; (3) Anodic machining; (4) Electrolytic polishing.

Arc Machining. While arc welding is widespread, machining by arc is relatively rare, due to rapid wear of the tool electrode, dimensional inaccuracy and extensive changes in the metallurgical structure of the work-piece. Nevertheless, steels can be machined by a process similar to oxy-acetylene cutting, oxygen being blown into the region of an electric arc through a hollow electrode. Friction disc sawing is sometimes facilitated by passing an electric current through the cutting area, so creating arcs. Non-ferrous metals are "cut" very fast by an arc and a jet of non-oxidizing gas mixture which blows away the molten metal.

More extensively used are arc disintegrators for the extraction of broken tools such as drills and taps. These disintegrators usually consist of an electric vibrator which makes and breaks contact between a brass or copper electrode and the broken tool. When the current passing through the electrodes is interrupted, an arc develops and lasts until the contact is renewed. The core of the broken tool is thus eroded and the remainder can be removed from the work-piece. The operation is usually performed under a stream of water, and the disintegrator head can be mounted in the chuck of a drill press for better guidance. The erosion of the two electrodes (the broken tool and the copper rod) is caused mainly by the melting and vaporizing action of the arc, and therefore the method is regarded as arc machining. The heat developed is intense and the eroded surface is changed considerably in structure. While this method is most useful for the removal of broken tools, it is not accurate enough for precise copying as required in tool-making and similar work.

A typical disintegrator working from a safe d.c. supply is shown in Fig. 11.1. When the coil is energized, the iron core is drawn upwards, thus breaking the contact between the copper rod and the tool, causing arcing. As the circuit is broken, the spring moves the core downwards, a new contact is made and the cycle is repeated.

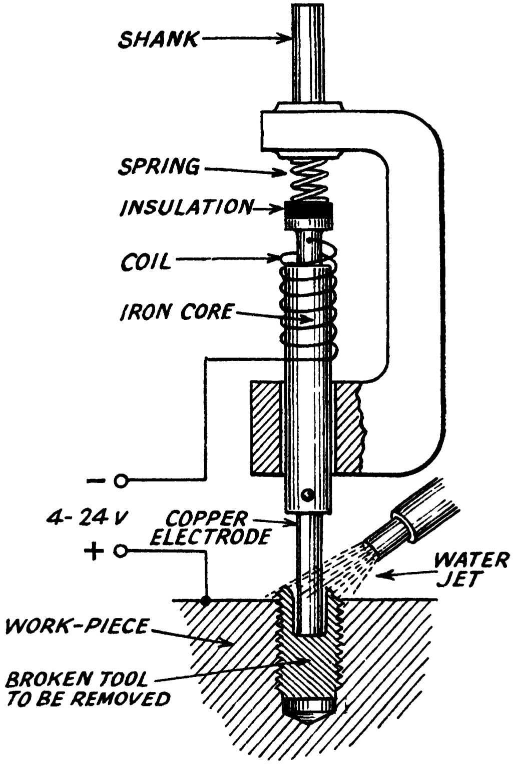


Fig. 11.1. Diagram of a d.c. arc tool disintegrator

The frequency can be varied by adjusting the spring. Similar machines working from one of the standard a.c. supplies use transformers.

Spark Machining sometimes called spark erosion, is probably the most versatile electrical machining method in use. The cutting action is actually erosion caused by the passage of an electric spark. The process is performed in a liquid dielectric, usually paraffin or a light oil. Any material, whatever its hardness, can be machined provided it conducts electricity. This process is extremely useful, therefore, in tool making, since hardened steel and carbides can be machined with ease. Many other applications are possible and there is a wide scope for ingenuity; e.g. drilling tiny holes 0·005 in. diameter in fuel injection nozzles is successfully performed by spark machining. Another unusual application is cutting light-metal honeycomb sandwiches, trepanning rectangular holes in thin valve sleeves or "drilling" holes with curved axes. As there is no mechanical contact between the tool and the work-piece, there are practically no cutting forces and both the tool and the work-piece can be quite flimsy, especially when fine finishes and small rates of metal removal are involved.

Another advantage is that the tool may be made from a soft material, such as copper or brass. The main disadvantage is the wear on the tool itself, but generally this may be overcome by using a suitable technique.

The method is mainly used for drilling, broaching, engraving, embossing, thread cutting (internal and external) and similar operations required in tool and die making. It may also be applied in ways similar to turning, milling and grinding.

The liquid dielectric serves a dual purpose: it prevents particles of the work-piece adhering to the tool electrode, and greatly increases the rate of removal of metal as compared with operating in air.

In "spark-toughening" the adhesion of particles of metal to the cathode is utilized for coating, no liquid dielectric then being used.

PHYSICAL BASIS OF SPARK EROSION. When two electrodes are separated by a dielectric, either gas or liquid, and a suitable voltage is applied, the dielectric will break down. The strong electric (electrostatic) field produces a cold emission of electrons from the cathode and these cause ionization of the gap. An avalanche of electrons and ions follows, the resistance drops and the electric energy is discharged, causing electrical breakdown. This is a very much simplified statement, for the complete mechanism of the breakdown is quite complicated and not yet fully understood. The phenomenon occurs within a few μ sec., is accompanied by a shock wave in the dielectric, and the impact of the electrons on the anode causes transient pressure of hundreds of thousands of lb./in^2. The current density in the spark channel is of the order of 100,000 A/cm.^{2}, and the power developed at a staggering concentration of the order of 500 MW/cm.^{3} The temperature of the spot hit by the electrons may reach tens of thousands of ° C. As a result, the metal will melt, part of it will even be vaporized, and it will be ejected into the gap by electrostatic and electromagnetic forces.

If the gap is in air or gas, the anode particles will actually adhere to the cathode—the effect utilized in spark toughening—but liquid dielectric prevents this adhesion.

As the spark channel becomes full of ions and electrons emitted by the hot electrodes, its resistance drops to only a few hundredths of an ohm, and if all the energy stored in the circuit has not yet been spent, an arc will develop. In arcing, the current density is only a few thousand A/cm^2 and the temperature of the electrode surface about 4000 ° C; eroding action is much slower, and the heat penetrates into the electrodes much deeper than does a spark. Arcing, therefore, should be eliminated as far as possible.

An important feature of the spark-erosion process is the effect of the dielectric. The amount of metal eroded when using liquid dielectric is ten or more times larger than the amount eroded when using a gas-filled gap, other conditions (material of electrodes, voltage, energy stored) being identical. A possible explanation is that the liquid dielectric constricts the spark channel and so intensifies the erosion. The dielectrics used are paraffin, transformer oil or their mixtures. The rate of erosion varies only slightly with these liquids. Water can also be used, but because of its electrical conductivity, the erosion is only about 40 per cent of that for paraffin. To prevent fire when using inflammable liquids, the sparking zone must be well submerged, a layer of 1 in. of paraffin usually being adequate.

The erosion takes place on both electrodes, anode and cathode, but not to the same extent. As one would expect, the cathode wears less than the anode, and for that reason the cathode is, even if made from softer material, made the tool electrode, and the anode the work-piece. The proportionate rate of erosion of a copper tool on a hardened steel work-piece is 15 to 20 per cent.

Effects on Metal. A single spark produces a saucer-shaped crater, i.e. a spherical impression, the depth being 1/30 to 1/3 of the diameter. The shape, however, varies with different materials.

The surface produced by sparks is fairly uniform and non-directional. The size of the craters, and the surface finish, vary inversely with the rate of removal, the lower rates giving the better finishes.

For a given voltage U, there is a relationship $H_a^3 = KCU^2$ where H_a is the centre-line average. K is a constant and C the capacity of the discharged capacitor (in a relaxation circuit).

A surface finish of 30 μ in. average (or r.m.s.) can be obtained without difficulty, and with care it may be improved to about 12 μ in. and better. Fine finishes require a very slow rate of removal.

There are pronounced physical and chemical changes in the thin surface layer of the spark-machined metal. In steels, (even in mild steel) a high-carbon, hardened layer is formed, the carbon being derived from the cracked paraffin, and diffusing from deeper layers. The hardening is caused by the quick cooling action of the bulk metal, the dielectric having little effect here. It is possible to harden the surface of annealed tool-steel using a copper electrode in air.

In the spark-machined metal there are also residual stresses of considerable magnitude, contained in a layer about 1/1,000 in. thick, even with very fine sparking. These stresses, however, do not seem to have detrimental effects on dies and press tools made by this method, such tools usually showing longer life than those made by conventional methods.

The spark-eroded surface has a dull, matt appearance even at its finest finish, and as a rule it is left like this, but it can be polished by the usual methods if required.

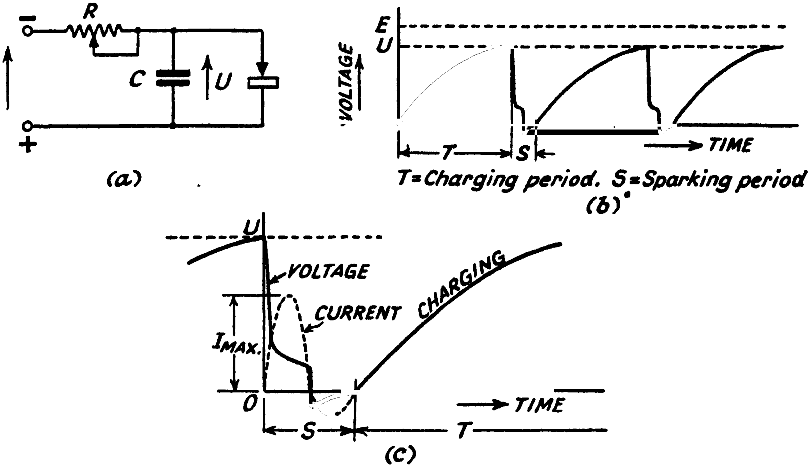
Equipment for Spark Machining. The generation of a succession of uniform electric sparks requires a suitable circuit. The one most used is a d.c. (usually rectified a.c.) operated relaxation circuit, sometimes with modifications, such as the inclusion of an inductance. There are, however, a.c.-operated relaxation circuits too, also pulse generators of various types.

The operation of the simple circuit, Fig. 11.2, is as follows: The capacitor is charged up to the breakdown voltage U, which is less than or equal to E, the voltage of the charging source. The breakdown voltage is controlled by the gap size, and when the breakdown occurs, a spark develops. The energy $\frac{1}{2}CU^2$ is liberated within a short period (from a few up to 1,000 μsec., increasing with the capacity C), and the capacitor is then recharged. After the time T another breakdown occurs, and as $U = E\{1 - \exp.(-T/RC)\}$, we have $T = -RC/\{\log_e(1 - U/E)\}$.

The number of sparks occurring in 1 sec. is N, which equals I/T or $-\log_e(1 - U/E)/RC$. Thus, for given values of C, U, and E, i.e. for a particular surface finish, the rate of removal varies inversely with the ballast resistance R.

On the other hand, the resistance R must be high enough to prevent arcing. It has been found experimentally that the highest rate of removal without serious arcing is obtained when R is adjusted in such a way that the ratio of the working current to the short-circuit current is from 0·6 to 0·8. Both currents are measured by an ammeter (not shown in diagram). The working or charging current is measured during continuous and stable sparking, and the short-circuit current when the electrodes are in contact.

The amount of metal removed by a single spark is approximately proportional to its energy, which equal $\frac{1}{2}CU^2$. The amount removed in 1 sec. is thus proportional to NCU^2. The maximum rate will occur when NCU^2 is maximum. This corresponds to a particular value of the ratio U/E. Both theoretically and experimentally, the best value for U/E is 0·7 to 0·9.



$U = 150$ v $C = 120$ μF
$I_{max} = 340$ A $S = 100$ μsec.

Fig. 11.2. (*a*) Basic relaxation circuit. (*b*) Voltage-time diagram of relaxation-sparking circuit. (*c*) Spark diagram

Since E is constant and determined by the equipment, U is the quantity to be varied, and this is brought about by adjusting the gap. It should be borne in mind, however, that the actual gap depends also on the electrode materials and the capacitance, the reason being that the dielectric is contaminated by metallic swarf which constitutes a partial electric bridge in the gap. The larger the discharge energy, the larger will be the amount of swarf in the immediate neighbourhood of the sparking zone, and in consequence the larger will be the gap required.

A typical unit for drilling, broaching and engraving will therefore have the following features:

(*a*) Means of adjusting the rate of removal in coarse working and a suitable fine-working range for finishing. These requirements are usually met by varying *R* and *C*. The heaviest machines provide for values of *C* up to 400 μF, as this is the limit of efficient application. Many types use much smaller capacitancies, up to a few tens of μF, and some not more than 1 μF, obtaining an appropriate rate of removal by a higher frequency of sparks.

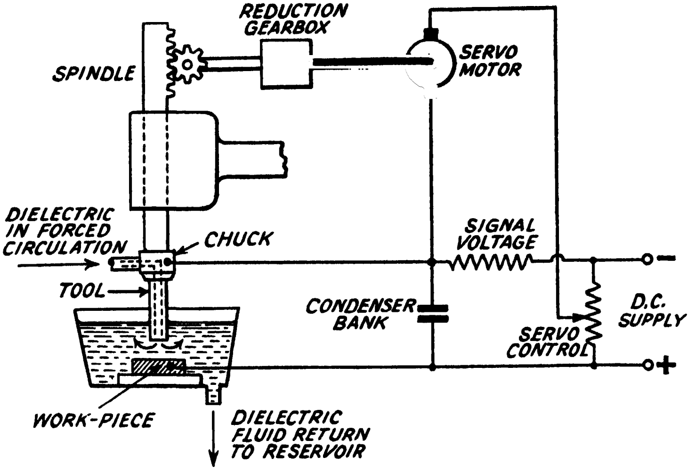


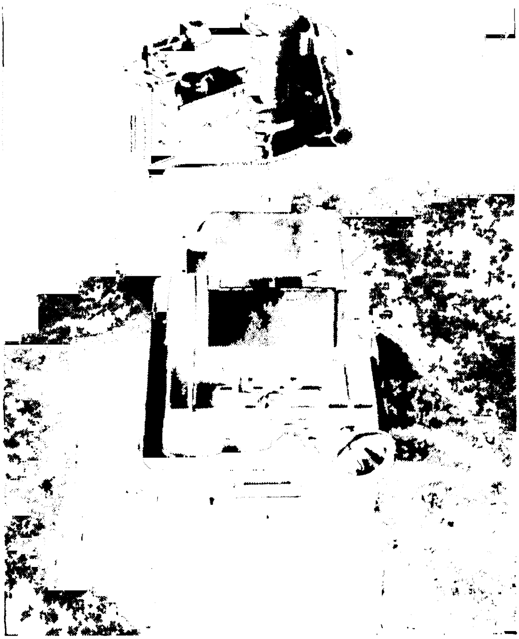
Fig. 11.3. Line diagram of spark erosion machine with servo system

(*b*) Means for keeping the gap at a constant width irrespective of the wear on the tool and the work-piece. This is obtained by a suitable servo-system, monitored by a preset value of the breakdown voltage *U* which controls the position of the tool electrode so as to maintain a constant gap.

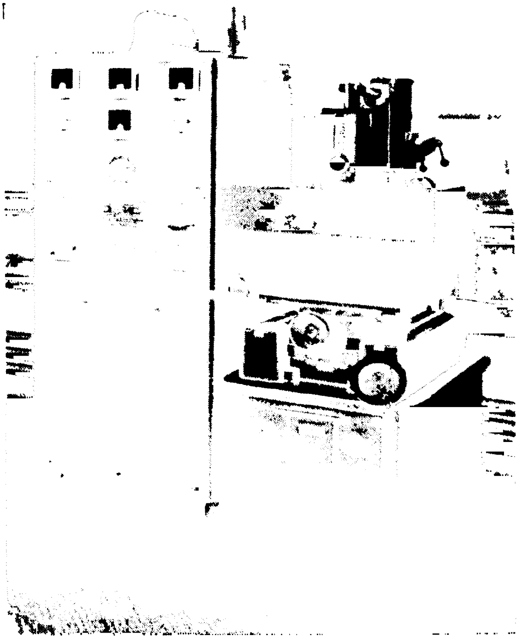
(*c*) A working table which can be submerged in liquid dielectric supplied by a circulating system to keep the dielectric in motion. As the swarf accumulates very quickly, the dielectric has to be filtered or passed through sedimentation tanks.

A typical unit is shown diagrammatically in Fig. 11.3, and a photograph of the apparatus in Fig. 11.4.

While these are the basic requirements, some machines have vibrating tool-holders which are said to facilitate the start of cutting. Others have automatic penetration control, arrangements for periodical withdrawal of the tool for intensive flushing of the produced cavity, arcing indicators and even cathode-ray oscilloscopes. Special servo-systems rotating the tool are used for thread cutting.



(*a*)



(*b*)

Fig. 11.4. (*a*) (*b*) A spark erosion machine

(*Impregnated Diamond Products Ltd.*)

Power requirements vary according to the purpose of the machine. Small tool and die-sinking units may require not more than 1·5 kW, while heavy plant used for the manufacture of forging and die-casting dies require 10 kW and more.

The maximum rate of removal in roughing is about 1/30 in.^3 of hardened tool-steel per minute for heavy machines and correspondingly less for small equipment. For operations to give good surface finish, the rate may fall to 1/1,000 in^3/min. and less.

The working voltage of contemporary units is usually above 100 V, the majority using 200 V and more. The price of a medium unit is at the time of writing about £1,000.

Technology of Spark Erosion. For proper utilization of spark erosion technique the following conditions must be borne in mind:

(*a*) There is always wear of the tool, proportional to the erosion of the work-piece.

(*b*) A high rate of removal produces poor finish, and good finish and accuracy can be obtained only at low rates.

(*c*) The spark gap is all around the tool so that the shape of the work-piece cavity is always larger than the tool electrode. The resulting clearance varies with the rate of removal, the materials of the tool and the work-piece. Different tools may be required for precise machining of different work-piece materials. Tools for finishing must be larger than for roughing. Tables 11.1, 11.2 and 11.3, show the effect on the side clearance, during broaching, of the rate of cutting, and of tool and work-piece material.

(*d*) The gap must not be clogged with swarf. This may require periodical withdrawal of the tool and a consequent drop in productivity. Whenever possible provision should be made to feed dielectric directly to the end-face of the tool, using either a hollow tool or one appropriately bored with feeder holes.

TABLE 11.1—EFFECT OF OPERATING CONDITIONS ON SIDE CLEARANCE WORKPIECE: NICKEL CHROMIUM STEEL. TOOL: BRASS (59% COPPER)

Rate of Cutting	*Finish Required*	*Side Clearance 1/1000 in.*
Rapid	Coarse	20—24
Medium	Medium	8—12
Very Slow	Fine	1·2—2·4

TABLE 11.2—EFFECT OF TOOL MATERIAL ON SIDE CLEARANCE AT A VERY HIGH RATE OF REMOVAL. WORKPIECE: HARDENED CARBON STEEL

Tool Material	*Side Clearance* 1/1000 *in.*
Brass, 59% Copper	10
Copper	11
Duralumin	12
Copper-graphite	14

TABLE 11.3—EFFECT OF WORKPIECE MATERIAL ON SIDE CLEARANCE. TOOL: BRASS

Finish	*Side Clearances—*1/1000 *in.*	
	Hardened Carbon Steel	*Hardened* 1% *Chromium Steel*
Coarse	5	6
Medium	4	5
Fine	2	2·6

TABLE 11.4—RATE OF METAL REMOVAL AND TOOL WEAR FOR VARIOUS TOOL MATERIALS. WORKPIECE: HARDENED TOOL STEEL

Tool Material	*Rate of removal* %	*Rate of wear* %	*Rate of removal* / *Rate of wear*
Brass (59% Copper)	100	100	1
Brass (62% Copper)	35	84	0·42
Phosphor bronze	65	69	0·95
Red Copper	70	37	1·9
Cast Iron	45	38	1·18
Copper-graphite	150	30	5

Electrode materials determine the rate of removal and the accuracy of machining for given electrical conditions. Table 11.4 shows the wear and rate of removal of various tool-electrode materials as compared with brass containing 59 per cent copper, 40 per cent zinc and 1 per cent lead. The material machined is hardened carbon tool-steel.

The best tool material is copper-graphite, but its poor mechanical properties make it difficult to machine satisfactorily; next best is copper and this is therefore used extensively. A copper alloy containing 96–97 per cent copper and the remainder cadmium, is even better, having a higher rate of removal for the same wear.

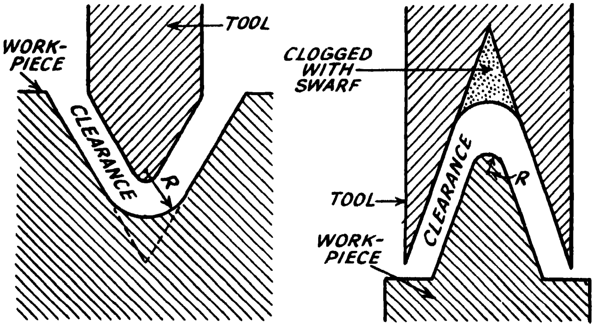


Fig. 11.5. Distortions in cavities and projections

Brass with 59 per cent copper has a high rate of removal and will frequently be preferred, e.g. where the tool is an extruded section and can be made long enough to compensate for higher wear.

Another consideration is the ease with which the tools can be made. Sometimes a casting material will be preferred so that the tools may be cast to shape. Cast iron and aluminium, for example, are sometimes used.

Accuracy. By accuracy we mean the amount by which the produced shape deviates from a theoretical one (i.e. the tool itself), the cavity in the work-piece being an "envelope" of the tool. Within the above definition the best copying accuracy achievable by modern equipment is about 0·0002 in. There is some difficulty in producing, without distortion, sharp cavities, projections and parallel holes, and some of these distortions are illustrated in Fig. 11.5, where 0·003 in. is about the nearest one can get to accuracy for the radius *r*.

Parallelism depends on the rate of removal, the nearest to it being obtained in finishing. Even then, however, the outlet width is always smaller than the inlet, and the slope is about 1/3 of a degree when using solid parallel tools for "through" holes.

During an actual piercing operation with a long parallel-sided tool, the tool-wear will largely be concentrated at and round the leading end, which will be considerably shortened and reduced in width. It will also lose its corners and edges. When the piercing is complete the tool will pass through the hole and further sparking will occur between the sides of the hole and the relatively undamaged flanks of the tool. Though this will greatly reduce the taper and lack of form of the hole, there will be some lateral tool-wear on passing through the hole and, in consequence, some taper of the hole itself is unavoidable. This taper is sometimes utilized as draft in dies.

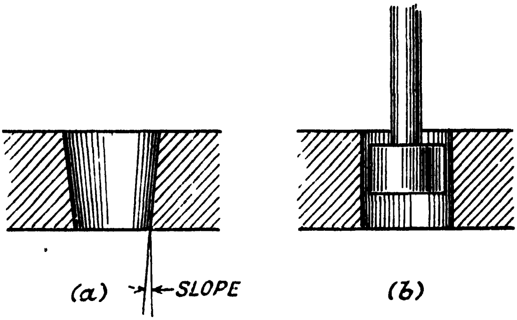


Fig. 11.6. (*a*) Slope (exaggerated) obtained by solid parallel tool. (*b*) Disc tool for correcting parallelism

For better results tools must be short and disc-shaped, and the hole should be broached several times with successively larger tools (Fig. 11.6). Mounting the tool with its axis parallel to the spindle axis is of course very important.

Sometimes it is possible to use the same tool for broaching and finishing of through holes, and when this is done the lower, roughing part is reduced in cross-section, usually by etching (Fig. 11.7).

Tools. The tools for broaching are usually solid rods of the required cross-section, and for engraving, the inverse shape of the required cavity. For broaching larger holes, however, hollow tools are more economical, the inner space then being force flushed (Fig. 11.8). In reconditioning forging dies the actual forged product can be used as the tool.

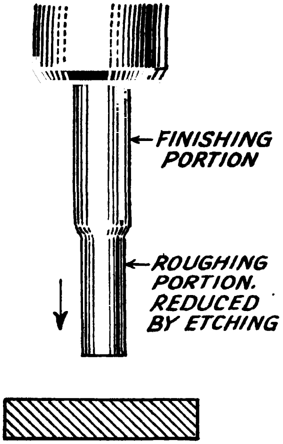


Fig. 11.7. Broaching tool with roughing and finishing portions

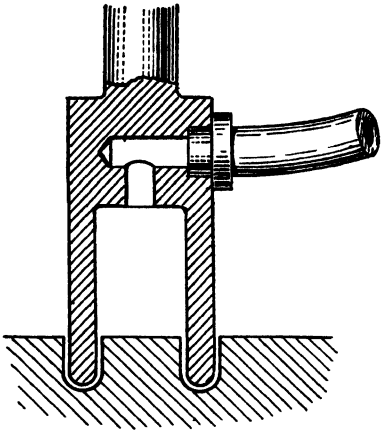


Fig. 11.8. Trepanning tool with forced circulation

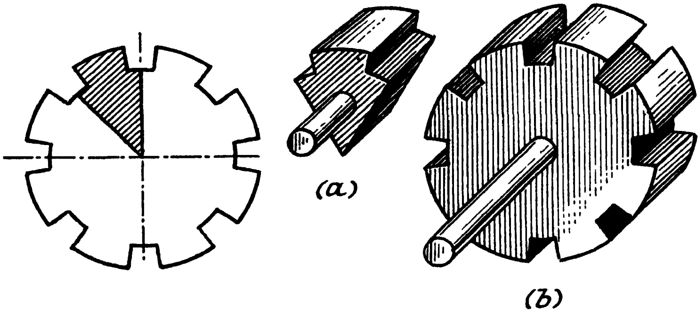


Fig. 11.9. Segmental and full profile tools

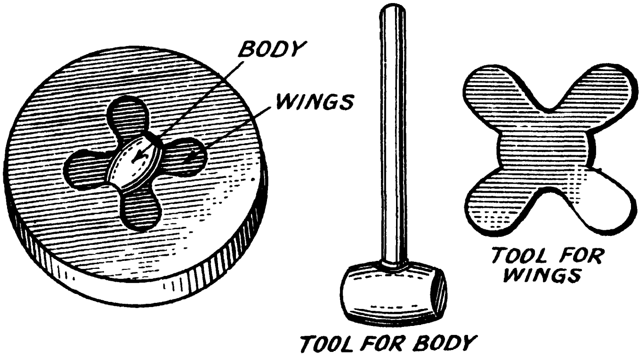


Fig. 11.10. Die for stamping wing-nuts. Tools for making the die

Segmental tools, Fig. 11.9, can also be used, especially for working complex holes that do not require close accuracy. It is sometimes easier to produce a cavity by using a series of simple tools, than by employing a single, complicated one (Fig. 11.10). Forced circulation for flushing should be employed whenever possible; Fig. 11.11 shows a sinking tool with several small holes drilled for that purpose.

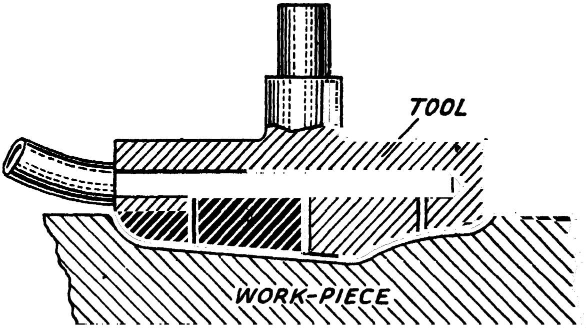
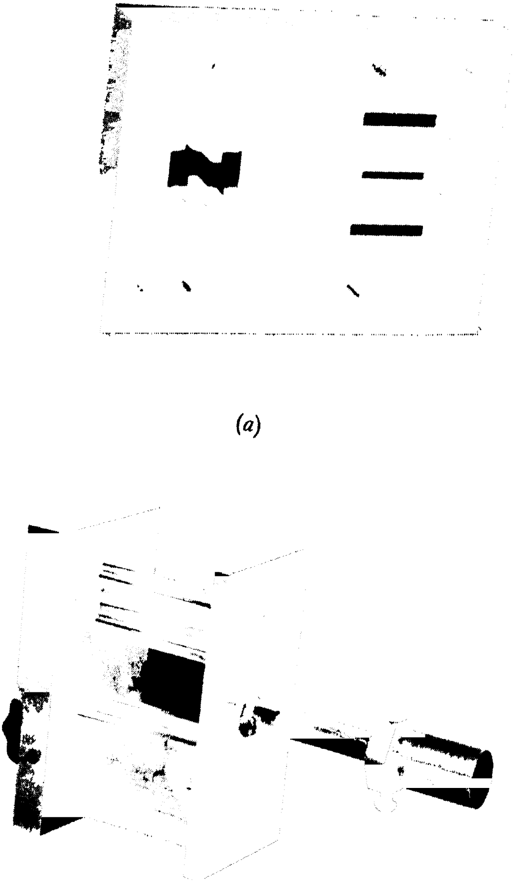


Fig. 11.11. Die-sinking tool with small holes for pressure flushing

The relative rate of wear already referred to (20 per cent for a copper tool on hardened steel) increases when broaching holes below, say ¼ in. diameter. For very small holes of, say 0·01 in., the tool-wear may be 8 times the rate of work-piece erosion. A special feeding device is employed for use with such thin, wire electrodes since the usual machine head is too heavy.

Various work-pieces and the corresponding tool electrodes are shown in the following illustrations, and are reproduced by courtesy of Impregnated Diamond Products Ltd. of Gloucester. Fig. 11.12*a* shows a die plate and 11.12*b* the tool resting in the finished plate. Fig. 11.13*a* shows an internal gear broached by the tool shown (with the gear) in Fig. 11.13*b*. Another die, the tool and the pressings produced are shown in Fig. 11.14. The concentration of tool-wear over the leading portion of the tool and the relatively undamaged tool section used for the final sizing after complete penetration had been achieved, will be noted. Fig. 11.15 shows forging dies with the tool electrodes. Fig. 11.16 is a thread-forming tool with the tool-electrode used in making it. The fineness of detail that can be reproduced is illustrated in Fig. 11.17. In such, several tool-heads may be employed in succession so that tool erosion during the final finishing process may be very slight.



(a)

(b)

Fig. 11 12. (a) A die-plate. (b) Tool for making the die-plate

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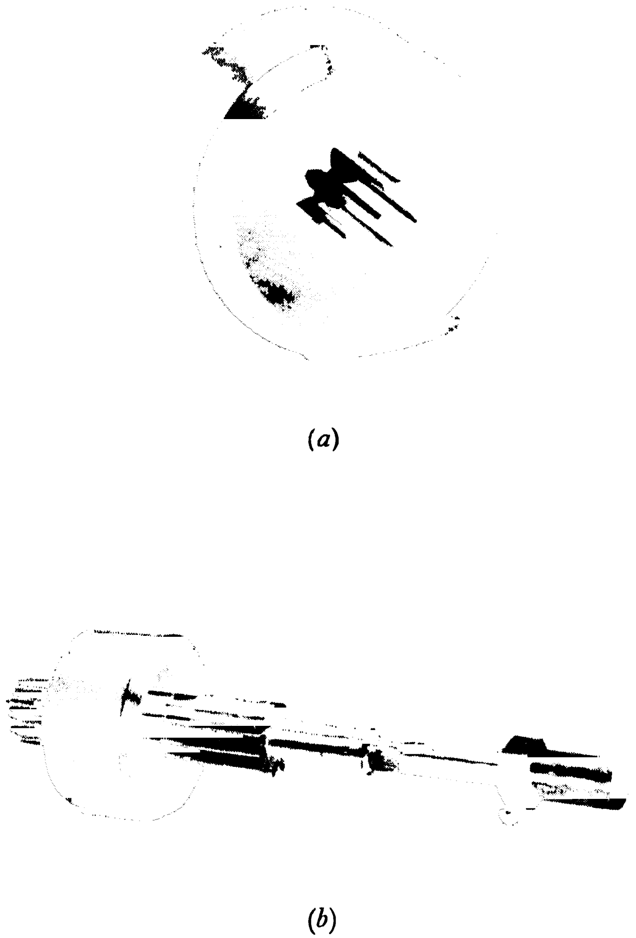


(a)

(b)

Fig. 11.13. (*a*) An internal gear. (*b*) Tool for making the internal gear

Fig. 11.14. A die, tool electrode and the pressings

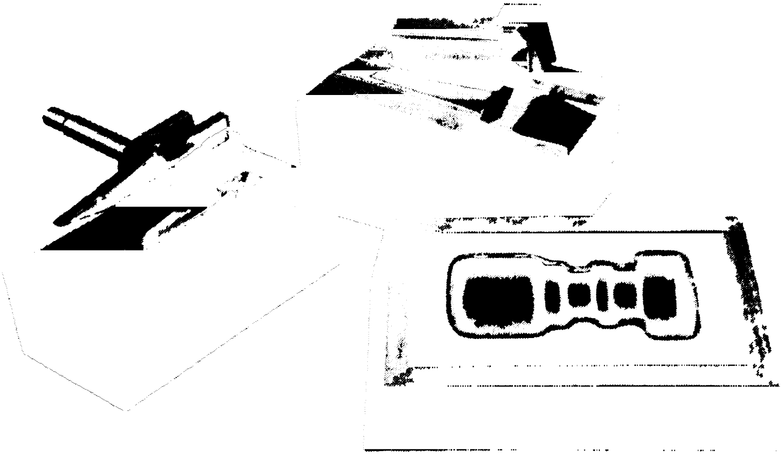


Fig. 11.15. Forging dies with the tool electrodes

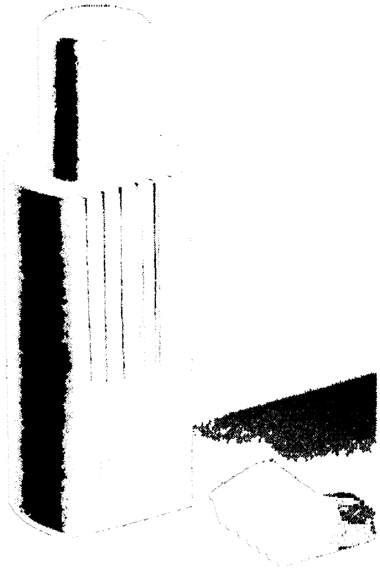


Fig. 11.16. A thread-cutting form tool with the tool electrode
(*Impregnated Diamond Products Ltd.*)

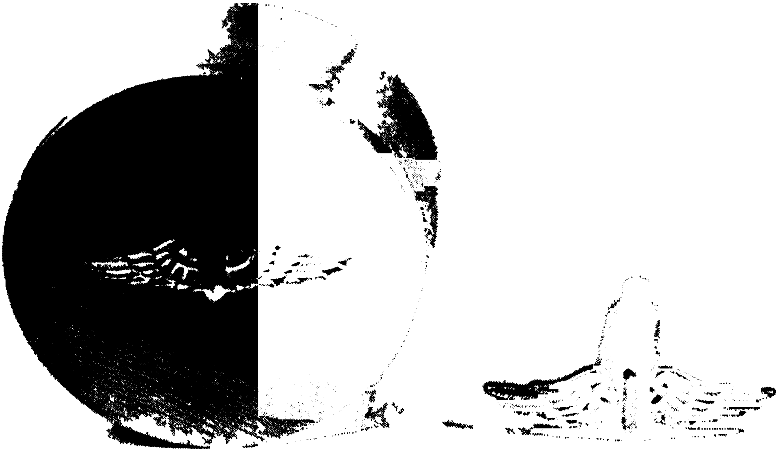
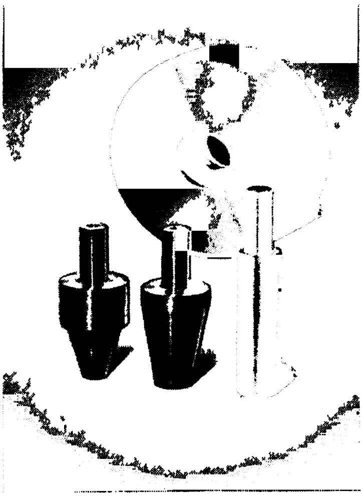
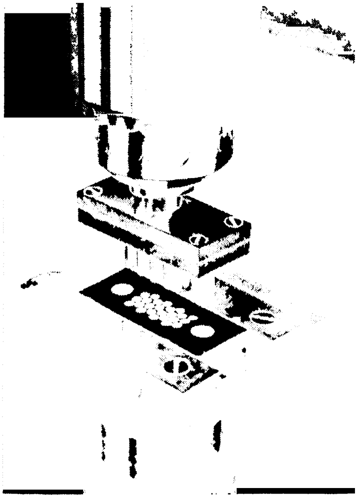


Fig. 11.17. A die with fine details



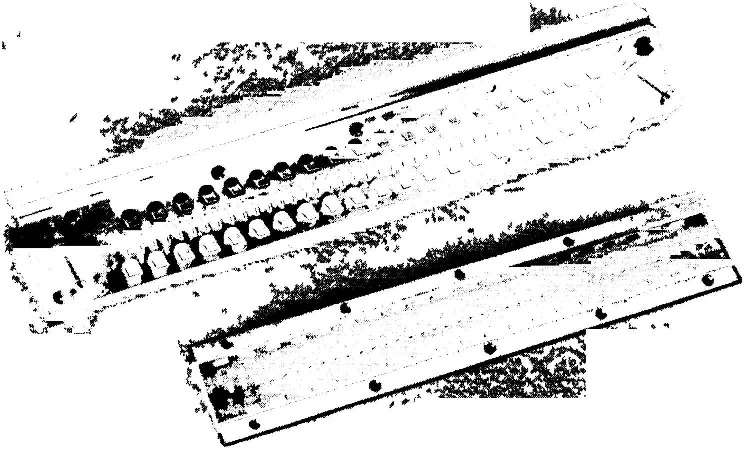
(a)



(b)

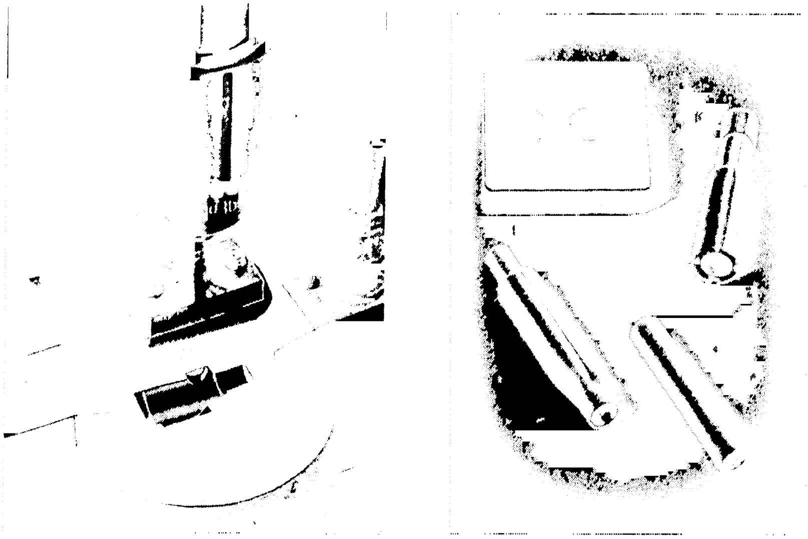
(*a*) Three different types of electrode, all brass, were used in forming this tungsten carbide drawing die of [illegible] in bore and [illegible] in through depth. First the parallel bore was eroded on two settings, medium coarse and fine, whose traces are visible on the parallel electrode. The entrance radius and exit angle were then eroded with the other two electrodes. The tolerance on the finished die was 0.0005 in and the total erosion time 14½ hours.
(*Wickman Ltd*)

(*b*) In producing 24 relief holes and two dowel holes in this tungsten carbide piercing die the first operation pierced the dowel holes right through and the relief holes to 0.17 in deep. Then the dowel holes were accurately sized and the relief holes 0.059 in diameter eroded right through the die plate from the back. The first operation, at the medium coarse setting, took 2 hours 35 min, and the second, at the medium fine setting, took 1 hour 30 min, making the time for the complete operation 4 hours 5 min.
(*Wickman Ltd*)



(c)

This precision radar component, in 0.018 in thick brass, has slots 0.157 in by 0.040 in which had to be kept to a limit on slot width of 0.0002 in and an overall pitch tolerance of 0.001 in. The electrode assembly, made up from replaceable brass inserts bedded in Ceromatrix, was used for three components before replacement. The erosion time for each component was 24 min, as against about 50 hours by previous machining operations.
(*Wickman Ltd*)



(*d*) (*e*)

(*d*) Ten electrodes were used to sink this die for gas tap bodies in a total time of 5 hours 47 min. 4 electrodes were used at the coarse setting, 3 at medium coarse, and 3 at medium fine. (*Wickman Ltd*)

(*e*) This special tungsten carbide component has asymmetric shapes round the circumference of the circular internal form which is 1 in. deep and 3 operations were necessary for its production. First the core hole was trepanned at the coarse setting with a tubular brass electrode and the form was then semi-finished at the medium coarse setting leaving about 0.004 in. thickness to be removed by the finishing operation. This was performed on the fine setting, the complete operation taking 20 hours. (*Wickman Ltd*)

(*f*)

Trolley wire die with Wimet nib. This form, entrance and exit angles, was eroded from a Wimet piece which had been sintered with a $\frac{3}{8}$ in. bore. The form was completed to within 0.008 in. of final size in 10 hours. Complete manufacture by normal processes would take some 80 hours, using erosion, 25 hours. (*Wickman Ltd*)

Fig. 11.18

ECONOMY. The main advantage of the spark erosion method is that it facilitates the machining of hard metals, and thus introduces a new technological approach to an old and costly method of production. For example, the conventional method of making narrow blanking dies would be to design split dies, which would need to be machined, hardened and perhaps ground before assembly.

Similarly, carbide blanking dies or form-cutting tools of complex shape are very expensive to make in the ordinary way, and it is almost impossible to make carbide forging dies. By the spark erosion method, however, narrow blanking dies are made simply by cutting into a solid block of *hardened* steel or carbide, and the problem of making carbide dies is reduced to that of making one or more brass or copper tools.

As a very general guidance it may be said that spark-machining produces a blanking or a drawing die, or a form tool *in carbide*, at about the same cost as the conventional method produces it *in steel.* Considerable saving is also achieved when employing spark erosion to make or recondition dies and tools made of tool steels. The actual saving depends on the nature of the work and is greater for the more complicated shapes. As much as 40 per cent in labour cost may sometimes be saved. Another very important feature is the increased life of the harder dies, some forging dies showing increased longevity of up to 50 per cent.

Cutting tools also may be ground and sharpened by spark-erosion grinders, the cost for treating carbide steel tools by this method being equal to that of diamond lapping but with the advantage of an increase in life.

Six examples of work produced by spark erosion, with the corresponding machining times, are shown in Figs. 18*a-f*, these and the data being reproduced by courtesy of Wickman Ltd.

ADAPTING LATHES OR GRINDING MACHINES. Spark erosion may be performed on either of these. A diagram of a lathe adapted to this use is shown in Fig. 19*a*. Although it is possible to use a plain tool on the lathe or grinding machine, such a tool would wear away quickly, and a rotating disc similar to a grinding wheel is therefore preferable (Fig. 11.19*b*). It should run perfectly true, the best speed for uniform wear being found by experiment. There is no need to run it as fast as a grinding wheel since the speed has no effect on the rate of removal of metal, and merely induces vibration. The workpiece should rotate at not less than about 200 rev./min., the number of rev./min. seemingly being more important than the surface speed.

The negative pole of the discharge circuit is connected to the tool, the positive to the work-piece, both by means of suitable carbon brushes. The current must not pass from bearings to shafts and spindles, or through slideways, otherwise these will be damaged.

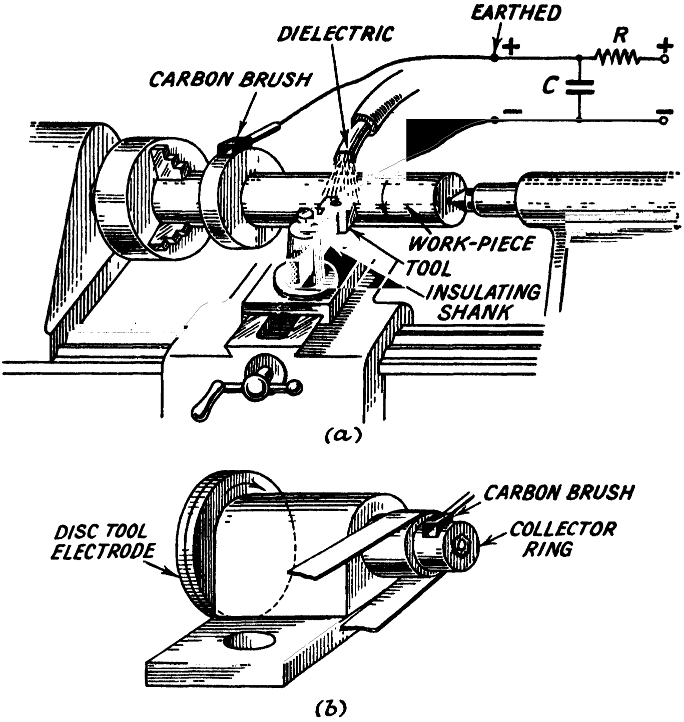


Fig. 11.19. (*a*) Diagram of a lathe adapted to spark machining. The tool is insulated from the tool post. (*b*) Device with rotary tool electrode for reduced wear

The electrical resistance of the discharge circuit must be kept as low as possible. The rate of removal falls very quickly with increase in resistance, as shown in the graph Fig. 11.20, which means that short, thick leads (flexible braids) and ample brush surface are necessary. Contact between the tool and the work-piece must be avoided since contact may cause serious inaccuracies in machining. The gap should therefore be as large as possible, which suggests that higher voltages are the most suitable. Not less than 100 V should be used for trouble-free machining. Suitable precaution must be taken to prevent electric shock to the operator. A similar adaptation to that shown for a lathe can be made on a cylindrical or surface grinder.

The dielectric is applied in a way similar to that for coolant, and it must be in copious supply. In all adaptations a non-inflammable oil is the best for this purpose; paraffin, if used, should be mixed with oil. It is sound practice to have suitable fire-fighting equipment near a spark-erosion machine.

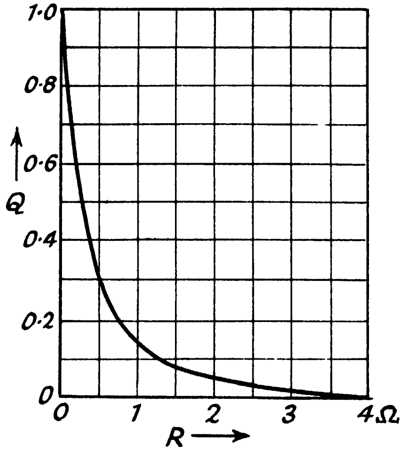


Fig. 11.20. The effect of resistance *R* in the discharge circuit on Q-rate of removal

No servo-mechanism is required for feeding the tool in turning or grinding. The gap is adjusted manually and all that is needed is a feed-screw with fine graduations, preferably 1/10,000 in., a feed that is a normal feature of any grinding machine.

TOUGHENING BY ELECTRIC SPARK. The process of toughening steel by electric spark is still in its infancy, and utilizes the adhesion of anode particles to the cathode when the spark occurs in an air gap. It is possible to obtain upon the cathode a coating of anode material in layers up to 0·003 in. thick. Carbon and high-speed steel-cutting tools may be coated by tungsten-titanium carbide and their life increased by two to three times, especially when machining high-strength alloy steels. Graphite electrodes greatly increase the hardness and the wear resistance of hardened carbon steel by increasing the carbon content of the toughened layer.

The equipment required for "toughening" is much simpler than that required for broaching, since no servo-mechanism or dielectric circulation system are necessary. The toughening electrode is vibrated by a simple 50-cycle vibrator and makes intermittent contact with the work-piece. A diagram of such equipment is shown in Fig. 11.21. The process may be used for toughening various cutting tools, drills, milling cutters, metal and wood saws, dies, rock drills, measuring instruments and gauges, machine parts and so on.

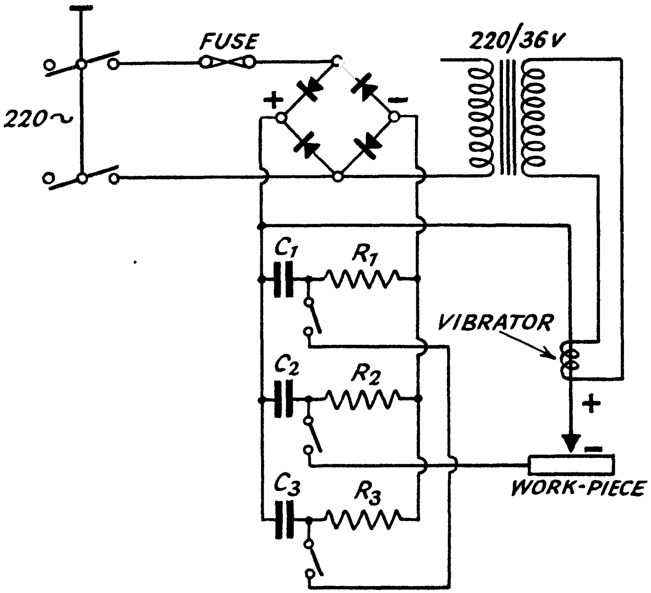


Fig. 11.21. Electrical system of a spark toughening apparatus

The toughening layer is usually ground after deposition, and it is sometimes lapped. When it has worn off it may be re-deposited. Typical data for a toughening apparatus are:

Power consumed, 0·8–1·2 kW.
Duration of toughening per 1 cm.^{2} surface, 0·5–3 min.
Duration of toughening of one cutting tool (15 mm.^{2}), 3–5 sec.
Consumption of energy for toughening 1,000 tools of $\frac{1}{8}$ in. by 1 in. shank, 1·2–1·5 kW–hr.
Consumption of tungsten-titanium carbide per tool, 2–5 mg.
Increase in tool life, up to 350 per cent.

Anodic Machining. This electrical method of machining is sometimes used for sawing or grinding carbide cutting tools and for lapping cylindrical carbide parts. Fig. 11.22 shows a diagram of an anodic saw. The cutting tool *a* is a mild steel disc 0·03 to 0·08 in. thick which revolves at a surface speed of 50 to 60 ft./sec. The workpiece is connected to the positive pole, and the tool to the negative pole of a d.c. supply of 10 to 30 V. The cutting zone is flooded by an electrolyte, usually an aqueous solution of water-glass.

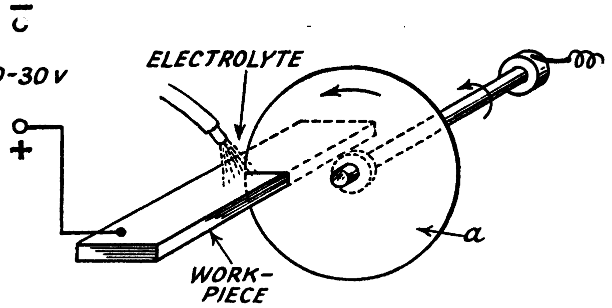


Fig. 11.22. Diagram of anodic saw

The cutting efficiency of this saw is high, for example, a 4 in. diameter steel bar may be sawn off in 6 minutes. The method is particularly suitable for sawing stainless and heat-resistant steels where its productivity is two to three times higher than that of mechanical sawing.

An anodic tool-grinder is shown diagrammatically in Fig. 11.23. The steel or cast-iron disc *a* is of 8 to 12 in. diameter, the working surface has narrow spiral grooves, and the surface speed is 80 to 100 ft./sec. The grinder can be used for roughing, finishing or lapping

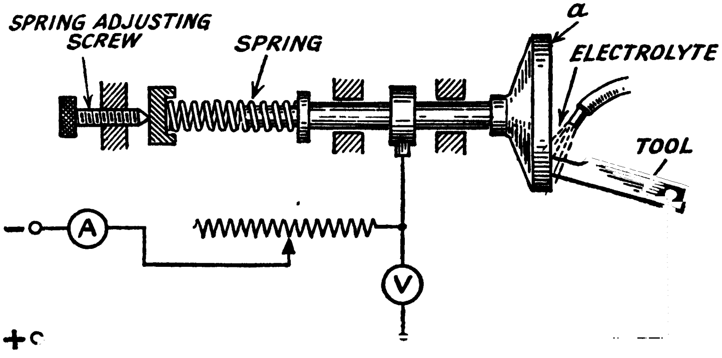


Fig. 11.23. Diagram of anodic tool grinder

according to the pressure between the disc and the tool (20 to 8 lb./in.^{2}). The pressure is varied by adjusting the spring. The best surface finish obtainable is comparable to diamond lapping.

The principle of operation of anodic machines is dual. At light pressures the action is mainly electrolytic, but at higher surface pressure, contacts are occasionally formed and the ensuing high current density melts small quantities of metal which are then removed by the fast rotating disc.

A development of the above method is electrolytic grinding with electro-conductive grinding wheels. The wheels are special, very porous, abrasive discs filled with graphite. The machining is performed on cylindrical grinders suitably adapted. The grinding action is brought about by electrolytic dissolution and the swarf is removed by the abrasive. The surface finish is as good or better than diamond lapping and is produced in shorter time.

Form machining cannot be easily done by anodic and electrolytic methods because the current density in the electrolyte is then non-uniform and is not subject to control.

Electrolytic Polishing. Basically a surface treatment, electrolytic polishing takes advantage of the fact that peaks are more readily dissolved than grooves, when subjected to electrolytic action. Electrolytically polished surfaces possess a characteristic lustre. To obtain real improvement in surface finish the preceding finish must not be too rough, otherwise the treatment will only result in a superficial gloss. It is possible to obtain a finish of 10 to 40 μ in. if the preceding surface is not rougher than 80 μ in.

The process is performed in an electrolytic bath which is the cathode, the submerged work-piece being the anode.

The limitations of the process, similar to those of the anodic machining process, are the non-uniformity of the rate of removal in formed surfaces and the inadequacy of control.

For Bibliography see end of book.

CHAPTER XII

SHEET METAL DRAWING

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With a Section on Load Conditions by
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Characteristics. Drawing may be defined as the process of forming a hollow article under the press from metal initially in the form of flat sheet or strip. This definition is not intended to include mainly bending processes mentioned in the next chapter. The distinguishing feature of a drawing operation is *surface distortion*, and the severity of such an operation is conveniently measured by the amount of this distortion; drawing is essentially a *straining* process which involves two-dimensional strain of the surface.

This strain is essentially plastic, and the forces involved in drawing depend on the stresses induced by this strain in the material in use. To predict these forces it is therefore necessary to understand its stress-strain relationship in the plastic region. This relationship is not simple and its application to drawing is difficult because strains vary from point to point and from stage to stage. In the relatively simple case of a cylindrical shell it has been found possible to compute the drawing load, and also the strains in the walls of the shell, but not so far those over the punch head. And since these are critical we are not yet able to predict the drawability of sheet from its stress-strain curve. In less simple cases of drawing our knowledge is almost entirely empirical.

In many drawing operations no direct attempt is made to modify or control the thickness of the sheet metal; any changes in thickness are caused by the strains imposed on the surface dimensions, and are conditioned by the fact that the density (and therefore volume) of any element of the material remains virtually unchanged under plastic strain. If, for example, an inch square, scribed on the sheet before drawing, is found subsequently to have become a rectangle 1·40 × 0·80 in. then the thickness will have diminished in the proportion 1/(1·4 × 0·8) = 0·89, that is, by 11 per cent.

A process in which the thickness is free from direct constraint may be called "pure drawing". On the other hand an operation in which the thickness of the metal is positively controlled by restrictive clearances between punch and die, is called an "ironing" operation. Thickness control can only be in the sense of thinning; thickening can only be produced as an indirect result of surface compression. In many drawing operations the processes of pure drawing and ironing are combined, but when the amount of pure drawing is considerable the ironing generally takes the form of "corrective ironing", which merely prevents the metal from thickening locally and so ensures a reasonably uniform thickness in the drawn article.

Principles of Drawing. These can be conveniently explained in terms of the simplest, probably the most common, and the most important drawing operation; the pressing of a cylindrical cup from a flat circular blank. Fig. 12.1. shows a circular blank resting on a die, kept in position by a blank-holder and being pressed into the form of a cup by means of a circular punch.

Clamped Drawing. If the edges of the blank are firmly clamped, so that they are unable to draw in, the punch as it moves forward will stretch the metal as shown in the figure, but will not appreciably alter the distance of any element from the central axis. If, therefore, we consider an elementary cube of the unstrained metal of side 100 units, and originally situated in the region of some point A, the shape of this cube when it has been stretched 25 per cent in one (originally radial) direction, while its dimension in another (peripheral) direction remains appreciably unaltered, will be as indicated in the figure, and its thickness will have diminished by 20 per cent since its volume is unchanged. The stresses induced by this system of straining are a high tensile stress in the direction originally radial, a more moderate tensile stress in the peripheral (hoop) direction, and no stress, of course, in the transverse direction. Hence, during an operation in which the edges are prevented from drawing-in the material is under an essentially tensile system of stress, and has a tendency to become progressively thinner at all points.

Free Drawing. Now consider the conditions that arise if the edges are not clamped, but free to draw between H and D towards the throat of the die. The diameter of each ring of material between H and D will diminish as the punch advances, and the *hoop* dimension will diminish in proportion. The diametral shrinkage tends to prevent a decrease in thickness and at the same time to increase the dimension in the originally radial direction, and so assist the drawing-

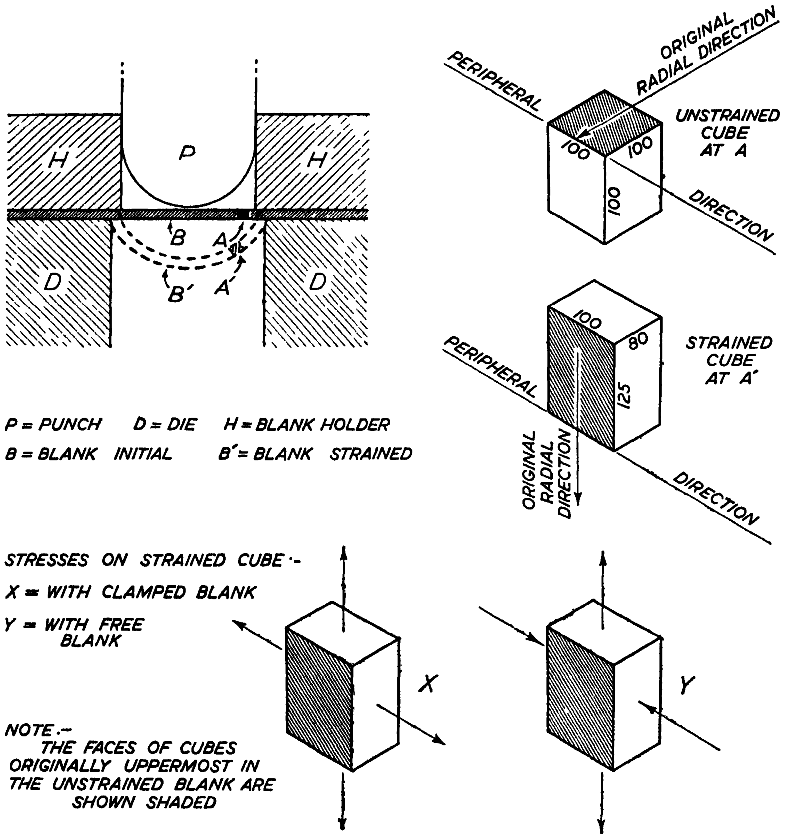


Fig. 12.1

in process; and the hoop shrinkage induces a *hoop compressive stress* which at the rim is actually equal to the *yield stress* of the material.

It is known that plastic flow occurs in a given material when the greatest difference between principal stresses reaches a value approximately the same as the yield stress in tension. Hence, in drawing, the existence of a high compressive hoop stress reduces the tensile stress in the radial direction necessary to cause flow; this compressive hoop stress constitutes the fundamental difference between the two types of drawing we have discussed. A more detailed examination of the problem will show that this compression in free drawing is greatest at the outer rim of the blank, while the radial tensile stress is greatest at the throat of the die. Consequently the metal near the rim becomes progressively *thicker* and that near the lip of the die tends to become *thinner*, though not to the extent which would occur if the outer rim were clamped.

With either type of drawing the conditions over the head of the punch are determined by the *radial tensile stress* necessary to induce the drawing action. These conditions are essentially tensile, so there is always a tendency towards thinning in this part of the metal. The conditions are also tensile in the parallel walls of the partially drawn cup, the tensile stress here being that required to transmit the punch load and maintain the drawing process. In free drawing, however, as the metal of the walls has already been drawn from a greater radius, its resultant thinning is less than that over the head of the punch. The resultant strains which develop during the free drawing of a typical cup are indicated in Fig. 12.2. Whereas the metal from the rim A thickens by 30 per cent, that round the head of the punch C becomes thinner by a similar amount.

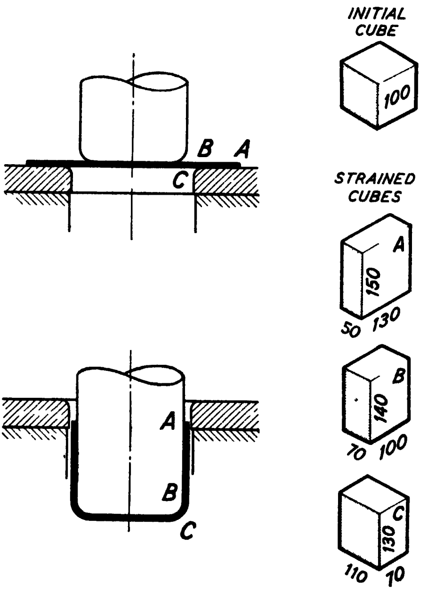


Fig. 12.2. Typical drawing strains

Puckering. The comparison between *clamped drawing* and *free drawing* will have shown that the tensile stresses and the tendency for thinning to develop are both far greater with the former, which is essentially a *stretching* operation and may bear this name. It is not surprising therefore that it is limited in practice, to relatively shallow draws. Within this range, however, it is very useful because it is free from the tendency to *puckering* which occurs under hoop compression.

Sheet metal under simple compression in the plane of the sheet is very liable to buckle; this tendency is diminished either by tensile stress in the perpendicular direction, or by compression across the thickness of the sheet. In practice puckering is commonly suppressed, without the use of excessive lateral pressure, by means of draw-beads, which produce a sufficient restraint to induce stretching and tend to iron out any incipient wrinkles. The shallow pressing shown in Fig. 12.3 is a good example; compare the puckering of the margins outside the draw-beads with the perfect surface within.

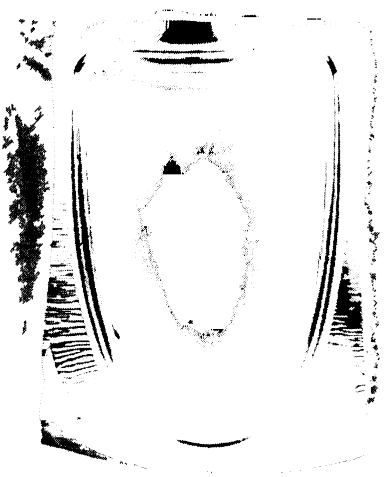


Fig. 12.3. Use of draw-beads to suppress puckering

STRFTCHING. The condition which determines whether a pressing can be produced by pure stretching, or whether it needs drawing in the technical sense, is the amount of stretching involved. Generally, it can be assumed that an operation which does not involve an extension in any direction greater than the general extension (before necking) found in a tensile test is suitable for stretching. Beyond this point it is necessary to provide some freedom for drawing-in.

These conditions suggest methods for comparison of the suitability of different metals for stretching operations. The general elongation in a tensile test is a useful criterion, provided that test-pieces are cut from the metal in such a way as to ensure that its ductility is adequate in all the critical directions. An alternative and simple form of test. which measures the same property in all directions at once, is the well-known Erichsen test, in which a sample of material is actually subjected to a general stretching operation, the edge of the blank being clamped. The depth of penetration of the punch at which rupture occurs is clearly a measure of the appropriate property, while the force required to produce rupture is a useful indication of the power required by the material in a stretching operation.

Clamping Pressure. The sphere of usefulness of the stretching operation in general press-shop practice is comparatively limited, and for most purposes it is necessary to permit drawing-in of the material. The suppression of puckering then becomes a primary problem unless the metal is comparatively thick in relation to its surface dimensions. For example, if the diameter of a circular blank exceeds about 25 times its thickness some form of blank-holding is necessary. Since any lateral restriction obviously tends to increase the force required to draw the metal, it is desirable to keep the pressure of the blank-holder to the minimum required to suppress puckering.

In practice two kinds of blank-holder are employed: one applies a positive and generally controlled pressure to the blank, the other provides a positive and limited clearance. Under ideal conditions the latter has advantages since it only exerts pressure when and where required, but it needs accurate setting and it does not accommodate the inevitable variations in blank thickness.

The positive pressure type, in which a constant blank-holding force is applied by means of some elastic medium (frequently a pneumatic air-cushion), is able to accommodate variations in blank thickness, but, since the pressure persists throughout the drawing operation whether or not it is required, it demands a higher drawing load, increases the tendency for the metal to thin, and limits the permissible depth of draw more than the positive clearance type. Nevertheless, present practice favours the pneumatic type, with the air-pressure adjusted by trial to the minimum value required to suppress puckering.

The necessary blank-holding force depends largely upon the shape of pressing. It may be 15–30 per cent of the drawing force in the case of a circular blank or up to 100 per cent for rectangular or irregular blanks. In this last case the puckering tendency may vary considerably at different parts of the blank, and the total blank-holding force may be substantially reduced if draw-beads are employed in those parts where the danger of puckering is greatest. Some variation in the severity of the draw-beads themselves can be achieved by altering their number and depth, or even by the discreet local application of lubricant to the blank in the press.

Drawing from a Flat Blank. Many deep articles requiring several stages of drawing are based on a circular cup as their first stage (Fig. 12.4). A general picture of the stress conditions which arise during the drawing of such a cup from a circular blank, and which determine the force required from the punch and the changes in thickness, which are so important, can be obtained by considering the forces acting on an element of a representative segment shown in Fig. 12.5.

The hoop compression p is primarily responsible for the reduction in circumference, and therefore in diameter, as the drawing proceeds, while t_1, t_2 represent the tensile drawing stresses in the radial direction. It is clear from the conditions of equilibrium of the element that the tension t_2 at the *smaller* radius is greater than t_1 at the *greater* radius, in order to balance the outward component of the hoop pressures p. Hence the radial or drawing tension must increase from the outer periphery, where it is zero, towards the lip of the die; and since the metal flows at (approximately) a certain value of the stress difference, $t - (-p) = t + p$, it follows that the hoop compression p will diminish from the outer periphery, where it coincides with the yield stress of the material, towards the lip of the die. It will also be clear that the greater the diameter of the blank in proportion to the diameter of the die, the greater will be the increase in t and the greater the diminution in p, and therefore the greater the value of t and the less the value of p at the lip of the die. Since this value of t at the lip of the die determines the force on the punch required to produce the plastic flow and continue the drawing process, it will be expected that:

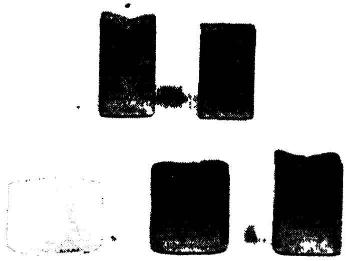


Fig. 12.4. Square container drawn from circular blank

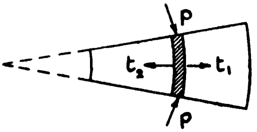


Fig. 12.5. Stresses in drawing from a blank

1. The punch force necessary for drawing will tend to diminish as the operation proceeds and the outer diameter becomes less.

2. The greater the initial diameter of the blank for a given die and punch the greater will be the drawing force required.

PUNCH LOAD. If the drawing force actually required is measured at various stages of the operation on a given blank the relation of drawing force to punch travel will be found to follow a curve of the type shown in Fig. 12.6, in which a number of sections have been inserted to show the profile of the partially drawn cup at several stages. The punch load actually rises at first before falling as expected. Comparison with the profile sketches will show, however, that this is because the walls of the incipient cup are not vertical during the early stages, so that the punch exercises a toggle action, the actual drawing stress in the metal being much higher than the punch force at first suggests. The initial rise in the curve is also partly due to the thickening of the material, and to the strain-hardening which occurs in all the metals used for drawing in practice.

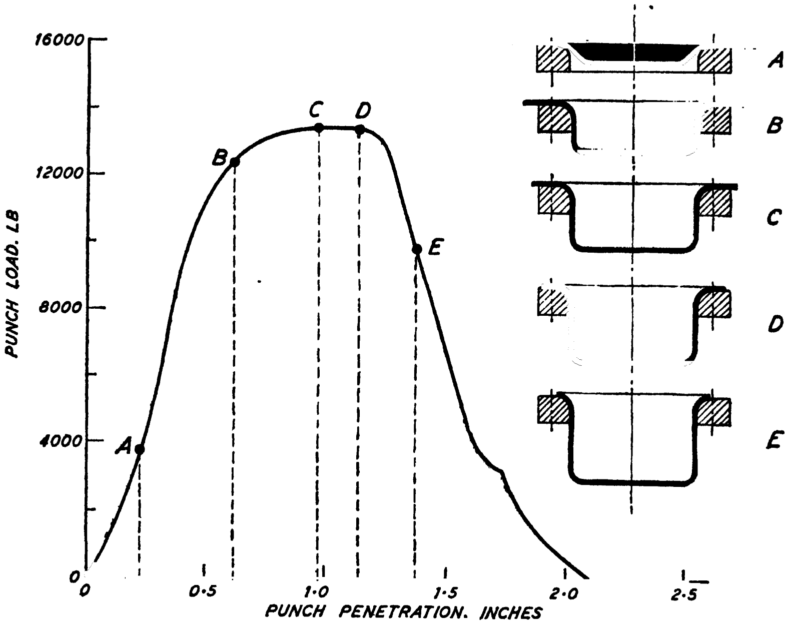


Fig. 12.6. Punch loads during drawing

The most important point of the curve is that giving the maximum punch load because if this maximum exceeds the strength of the cup walls, which have to transmit it from the punch head to the metal at the lip of the die, the cup will break. If the maximum punch load is measured for a number of blanks of different diameter, the punch and die remaining unchanged, the relation between punch load and blank diameter is very nearly linear (Fig. 12.7), rupture would occur with any blank requiring a greater punch load than that corresponding to the ultimate strength of the walls of the cup. In the figure this strength is about 14,000 lb. for *A* and *C*, and about 16,000 lb. for *B* and *D*.

Now *B* and *D* refer to a punch having a generous profile radius at its head, while *A* and *C* correspond to one having a rather sharp radius. Experiments have shown that a cup drawn with a sharp radiused punch is always weaker than one drawn with a punch of generous radius; the weakest part of the cup walls is that on the punch profile radius and the more severe the bending over this radius the lower is the strength of the metal.

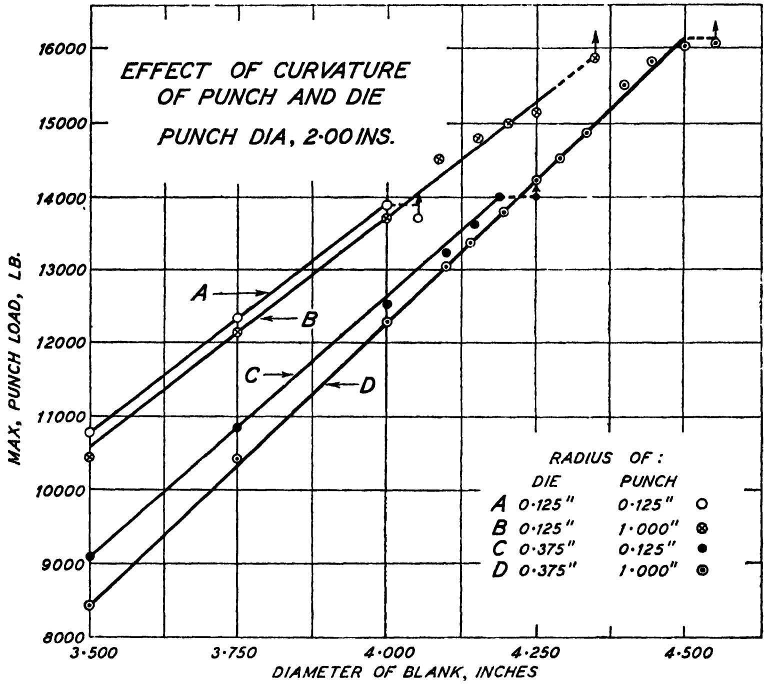


Fig. 12.7. Drawing loads

Die Radius. It will also be seen (Fig. 12.7) that the force required to draw from a given blank is virtually independent of the punch profile radius, but depends very much on the profile radius of the die. Lines A and B for a sharp die radius almost coincide and so do lines C and D for a more generous die radius, but the sharp radius requires substantially higher punch loads. It follows that a generous die radius is desirable to reduce the drawing load, while a generous punch radius is desirable to maintain the strength of the cup walls. An excessive die radius, however, may cause puckering, since the metal passing over this radius no longer has the restraining influence of the blank-holder.

Punch Radius. The changes of thickness which occur during drawing are greatly affected by the profile of the punch, as in Fig. 12.8, where the thicknesses at different points of a drawn cup are plotted for comparison with the punch profiles shown inset. The local thinning over the punch radius is very marked where the radius is sharp, while the hemispherical head produces a more general thinning over the base of the cup. The *least thinning* over the base occurs when a generous but not excessive punch radius is employed. It will be clear that the thinning at the lower end of the parallel walls of the cup has a weakening effect on these walls and, for this reason, a sharp punch radius gives a lower breaking load, as shown by lines A and C in Fig. 12.7. In contrast to the thinning in and near the base of the cups the outer parts of the blanks, which have become the upper walls of the cups, have thickened to the extent of 30 per cent, irrespective of the form of punch employed.

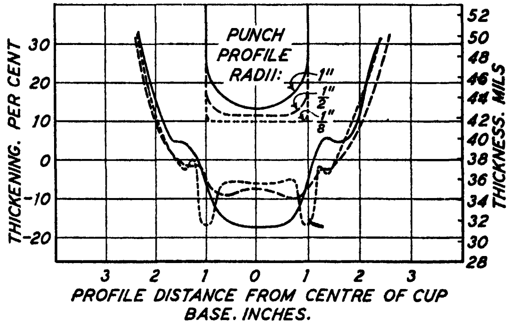


Fig. 12.8. Thickness changes

Drawing Ratio. The severity of a drawing operation may be defined either in terms of the ratio D/d of the blank diameter D to punch diameter d, the "drawing ratio", or by the "percentage reduction", $[(D-d)/D] \times 100$ per cent. The maximum possible drawing ratio varies considerably between different metals, the most suitable metals, of course, being those with the greatest permissible drawing ratio. In fact the suitability of sheet metal for a real deep-drawing operation can be conveniently measured by the maximum drawing ratio it will survive, and for this purpose a "cup-drawing" test is more appropriate than a stretching test of the Erichsen type.

The ultimate drawing ratio may vary from about 1·9 with an ordinary quality of aluminium to about 2·2 with a mild steel of average deep-drawing quality, and 2·3 with certain non-ferrous alloys. In practice these ultimate values are to be avoided, and a working ratio of about $1\frac{2}{3}$, corresponding to a reduction of 40 per cent, would be regarded as satisfactory.

Re-drawing. When an article is too deep to be drawn in a single operation from the blank it becomes necessary to re-draw the first-stage cup through a smaller die. It may or may not be necessary to subject the cup to some form of inter-stage heat treatment to anneal it and reduce its resistance to further plastic flow, but it will be seen shortly that such inter-stage treatment enables a greater reduction to be made in the *second*-stage operation.

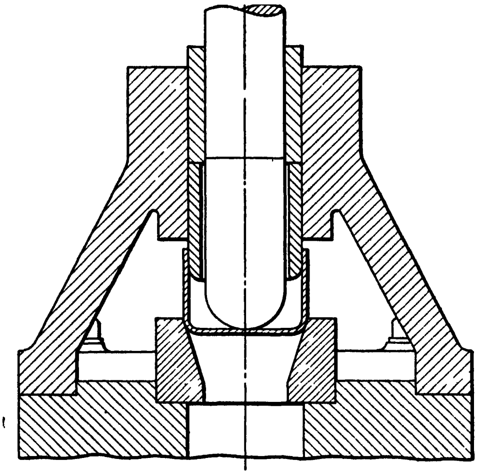


Fig. 12.9. Experimental tools for re-drawing operation

The blank-holding requirements for a re-drawing operation are generally quite different from those for initial cupping from a flat blank. The first-stage cup merely needs locating in the tools until the punch and die themselves take positive charge. For example, in the experimental sub-press shown in Fig. 12.9 the cup already formed is centred in the mouth of the die by means of a sleeve surrounding and concentric with the punch, which, however, merely penetrates a short distance into the mouth of the cup. By the time the punch has advanced sufficiently to draw the lip of the cup beyond the influence of the guide, the cup walls are effectively centred by the tapered face of the die, and by the head of the punch. Any pressure between the sleeve and the die through the walls of the cup serves no more useful purpose, but increases the drawing force and is apt to lead to premature failure.

Experimental work with dies of different profile angle has shown that a total included angle of about 30° gives the most satisfactory results.

Reduction. The degree of reduction successfully obtained in a re-drawing operation is considerably less than that obtainable in drawing from a flat blank. In practice a first-stage reduction of

40 per cent could only be followed by a re-drawing reduction of perhaps a further 20 per cent. There are three different causes:

1. The walls of the first-stage cup are thicker at the open end and thinner at the base than the initial sheet. Consequently a greater drawing force is demanded, while the strength of the lower walls which transmit the re-drawing force is reduced.

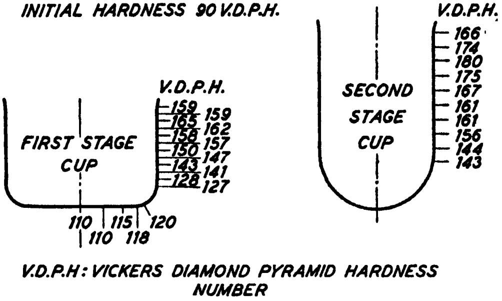


Fig. 12.10. Hardness changes in drawing and re-drawing

2. Unless inter-stage annealing has been carried out, the walls are harder in the upper part than near the base (Fig. 12.10), which further increases the re-drawing force.

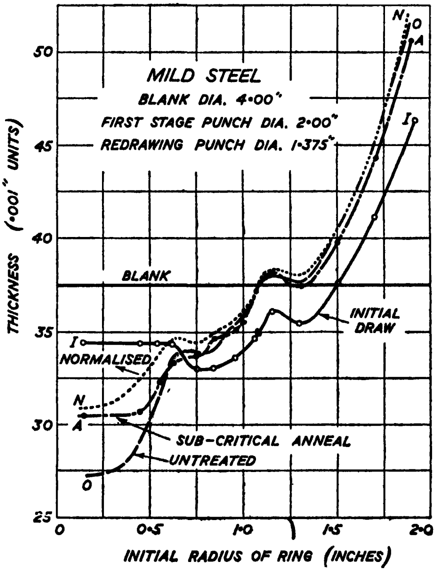


Fig. 12.11. Thickness changes in re-drawing

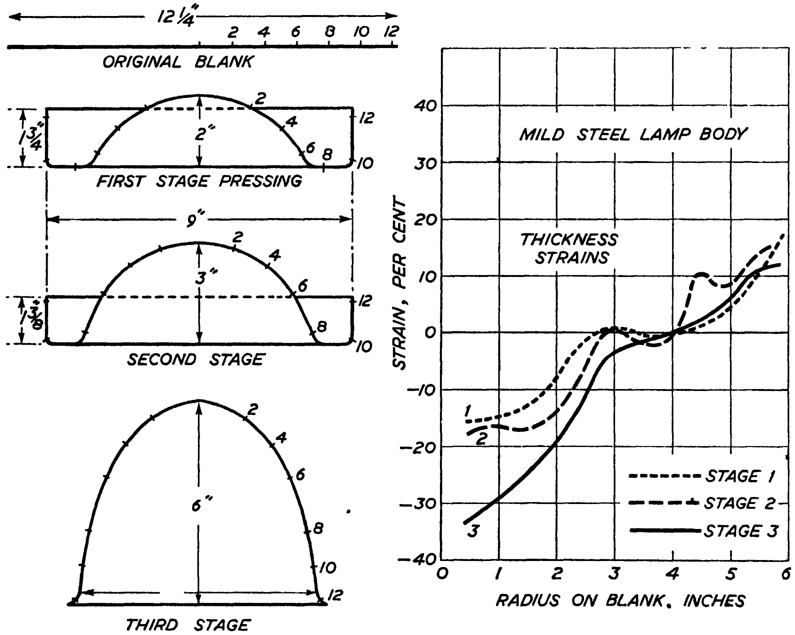
3. For some reason which is not at present fully understood, but which is probably associated with the bending of the metal at entry to the die, the intrinsic force required to reduce a tube of given wall thickness (and the re-drawing operation is essentially a process of tube-sinking) is much greater than that required to draw a flat blank of the same thickness over the same range of diameters.

Changes of Thickness. The practicability of any drawing operation depends very largely on the changes of thickness involved, and it therefore becomes important to examine the changes which occur during a re-drawing operation as well as those in the initial cup. These are well illustrated by the representative curves plotted in Fig. 12.11.

The initial draw was made with a punch of 2 in. diameter with a profile radius of ¼ in. Curve I in the figure corresponds generally to (half) the appropriate curve in Fig. 12.8, though the necking on the profile radius is not quite so marked. The re-drawing punch was 1½ in. diameter and had a hemispherical head, so that the operation is similar to that shown in Fig. 12.9.

The re-drawing operation produces a further thinning of the metal in the base of the cup but a thickening of the metal in all other parts, including the metal on the profile radius of the first-stage cup where necking had commenced. As a result the effect of this necking is largely obliterated by the re-drawing operation, and the critical region is transferred to the base of the re-drawn cup. If the first draw had been made with a hemispherical-headed punch, the metal in this critical region would have been thinner on entry to the second stage and the cup would have broken. Hence, a hemispherical punch has advantages for a single stage, or final draw, but is unsuitable as a preparation for further drawing.

The changes in thickness, which can easily be measured by

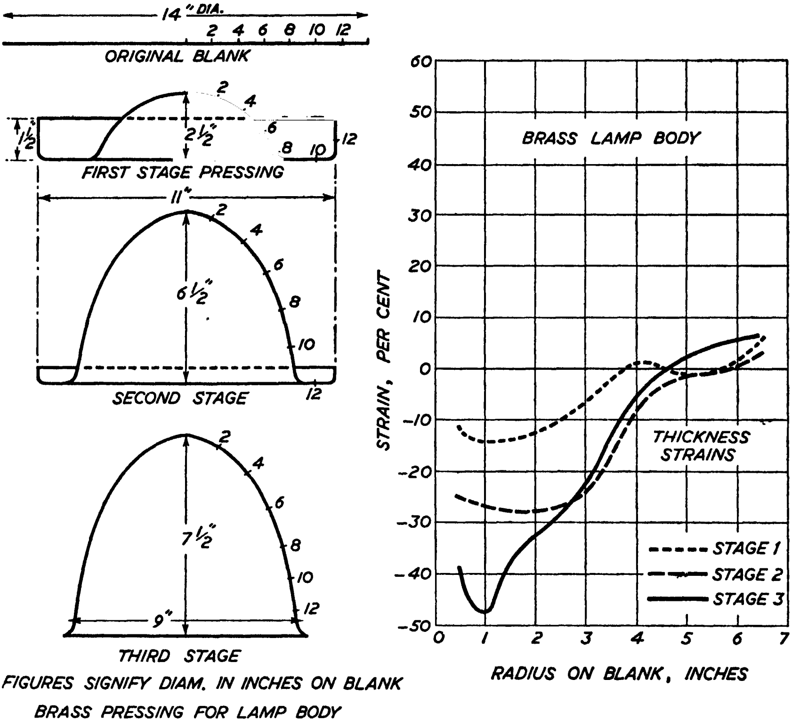


FIGURES SIGNIFY DIAM. IN INCHES ON BLANK

MILD STEEL LAMP BODY

Fig. 12.12. Thickness changes in three-stage draw (M.S.)

micrometer on a sample, are a very useful criterion of the suitability of a series of operations planned for the production of a deep pressing (Figs. 12.12 and 12.13). With the drawing schedule indicated in Fig. 12.12 it will be seen that while the thinning produced by the first and third operations is considerable, the second operation is relatively ineffective. On the other hand each of the three operations in Fig. 12.13 produces approximately the same degree of thinning, and the severity of the complete draw is evenly divided.



FIGURES SIGNIFY DIAM. IN INCHES ON BLANK

BRASS PRESSING FOR LAMP BODY

Fig. 12.13. Thickness changes in three-stage draw (Brass)

From the standpoint of plastic flow, therefore, the drawing schedule in Fig. 12.13 is superior to that in Fig. 12.12. Measurements of this kind should afford considerable help to the press tool designer in planning operations for a multi-stage draw.

In the second stage draw, the punch load required to reduce from a cup of given diameter is found by experiment, and confirmed by theory, to be approximately proportional to the reduction obtained (Fig. 12.14). It will be seen, moreover, by comparison of the two lines in this figure that the re-drawing load depends also (for a fixed re-drawing reduction) on the diameter of the original blank; because the larger the blank, the thicker and harder will be the metal in the walls of the first-stage cup.

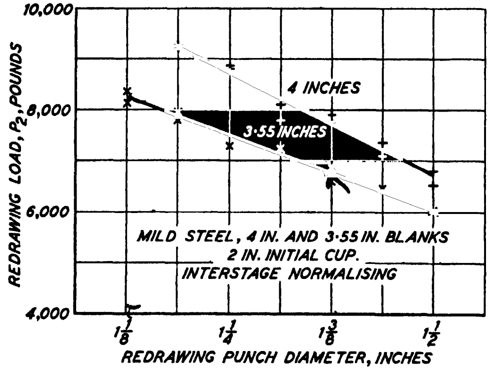


Fig. 12.14. Re-drawing loads

This leads naturally to the further conclusion, confirmed by Fig. 12.14, that less reduction is possible in the second stage when a large reduction has been obtained in the first stage, and this, again, raises the important question: Can a larger total reduction in the two stages combined be obtained by reducing the severity of the first stage in order to take advantage of the improved conditions for the second?

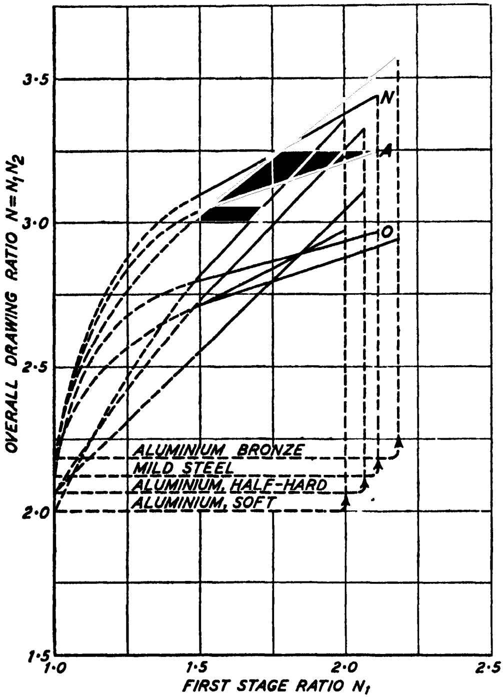


Fig. 12.15. Re-drawing characteristics

The answer is contained in Fig. 12.15, where the limiting combined drawing ratio, $N_1 \times N_2$, for two stages is plotted against the first stage ratio N_1, for a number of different metals. For each metal the curve rises as the initial drawing ratio is increased, showing that the greater combined ratio is obtained when the first-stage cup is drawn as deep as possible; so it would appear there is nothing to be gained by finesse in the planning of operations for a two-stage draw.

Multi-stage Drawing. The practicability of producing very deep articles requiring multi-stage drawing is largely determined by the two tendencies associated with any drawing operation: (*a*) the thinning of the metal near the base accompanied by the thickening of that in the upper walls and (*b*) the greater hardening of the upper walls as compared with the base.

These effects, unless they are controlled, are cumulative and will clearly limit the number of successive draws to which the metal can be subjected. The differential hardening effects can of course be minimized by inter-stage heat treatment, though this is expensive and not often used. The differential changes in thickness, although reduced by such heat treatment, are nevertheless progressive and produce a vicious circle (Figs. 12.12 and 12.13) from which there is no apparent escape in the free drawing processes hitherto discussed.

IRONING. This vicious circle can be avoided by either of two modifications in drawing technique. The first is "ironing", already mentioned, in which the clearance between punch and die is so restricted that the metal passing through is reduced to a uniform thickness throughout. This may be carried out without any concurrent reduction in diameter; or it may be combined with a drawing or re-drawing operation, when the *punch load* is necessarily increased but, since a large proportion of the additional ironing force is transmitted by compressive traction from the punch to the metal in the throat of the die, the *tensile stress* carried by the walls of the cup or tube is not increased in proportion. If the reduction of diameter is small, a reduction in wall thickness of as much as 50 per cent is possible, though not generally necessary or economical.

Where ironing forms part of the drawing schedule it is necessary, of course, to commence with a blank of considerably greater thickness than the walls of the final product, and this must be considered when planning the operation.*

In estimating the force required for an ironing operation without reduction of diameter it has been customary to assume that this force is proportional to some representative shear strength of the material, and to the cross-sectional area of reduction, so that the ironing load P is found by multiplying the reduction of area a by the so-called "ironing stress" f, or $P = af$. Recent theory, confirmed by systematic experiments, has shown that this procedure is fallacious.

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* See Lloyd, D. H., *Metal Industry*, **64** (1944), 34.

The *ironing load* is found to obey a law of the type: $P/A = c + bx$ where A is the initial sectional area of the walls ($\pi D t_0$) and c the proportional reduction in thickness $(t_0 - t_1)/t_0$, while b and x are constants for various reductions, but dependent on the die angle and the coefficient of friction. The constant c increases with the die angle, while b decreases. Typical relationships found experimentally for mild steel cups are shown in Fig. 12.16, plotted against the reduction of area $\pi D(t_0 - t_1)$ for various die angles. Until more complete data become available it is wise when planning ironing operations to make preliminary tests with the metal concerned over the range of thicknesses and reductions contemplated, with a die of suitable profile. It will be seen from the figure that a die of small angle is more economical for small reductions, and one of large angle is more efficient with large reductions. For use over a wide range of reductions a die angle of 10–15° is generally satisfactory.

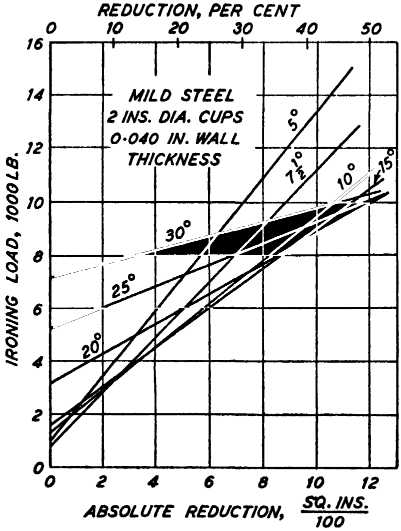

Fig. 12.16. Ironing characteristics for various die angles

It will be seen that the approximate law suggested above can be written: $P = cA + b\,(Ax)$, where Ax is the reduction of area; the greater the initial thickness of the walls the greater will be the ironing load for a given reduction of area. This fact is amply confirmed by experiment; it is found that ironing load increases with the wall thickness in quite a remarkable way. The load required, for example, to remove ·010 in. from the surface of a solid bar 2 in. in diameter is about five times that required to thin by the same amount the walls of a 2 in. diameter cup with an initial wall thickness of 0·040 in.

Pressure Sinking is the second remedy for the vicious circle of differential thinning. In this process the lower walls of the cup are relieved of tension altogether by transmitting the drawing force from the punch as a compression in the upper walls.

Fig. 12.17 represents one of seven similar stages in the drawing of a funnel;* in this process the punch does not penetrate to the base of the cup, but transmits its pressure through the flanges and so by compression to the walls of the cup passing through the die. When these walls have passed through the throat of the die they carry no load whatever, and the thickening inherent in the drawing process is not followed by any thinning, so that the walls of the resulting cup are thicker than the flanges and both are thicker than the original blank.

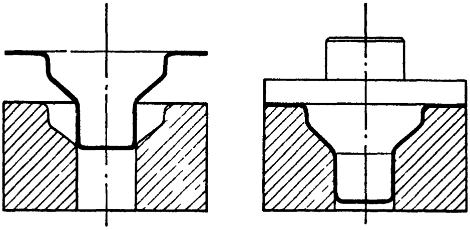

Fig. 12.17. Pressure sinking

In *contrast* to the *ironing* process it is therefore necessary to employ a blank thinner than the walls of the finished pressing, and a knowledge (or *ad hoc* investigation) of the degree of thickening involved is necessary when planning the sequence of operations. The process of pressure sinking is of rather limited application, because in practice it requires a flange on the pressing, through which the pressure can be applied, but it nevertheless deserves more consideration than it has received.

Non-circular Drawing. With the drawing of circular forms of pressing the problem of suppressing wrinkles is fairly simple, though the blank-holding pressure required may be sufficiently great in the case of large thin sheets to reduce appreciably the practicable drawing ratio. This problem is more troublesome in the case of non-circular pressings, and its solution often calls for considerable experience and ingenuity on the part of the tool designer. With a rectangular box, for example, the danger of wrinkling near the corners, due to the crowding of the metal in these regions, constitutes the main problem in the tool design and in the predetermination of the shape of blank.

In such a case the critical consideration is the relation of the depth of the draw to the corner radius, and it is a common rule to allow in the first drawing operation a corner radius not less than about one-fifth of the depth of the pressing. If the corner radius required in the final pressing is less than this it is necessary to redraw with successively smaller radii and slight increments in depth to contorm to the changes in radius. The number of operations required to reduce the corner radii depends largely on the way these operations are planned.

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* See Jones, F. D., *Die Design and Diemaking Practice.*

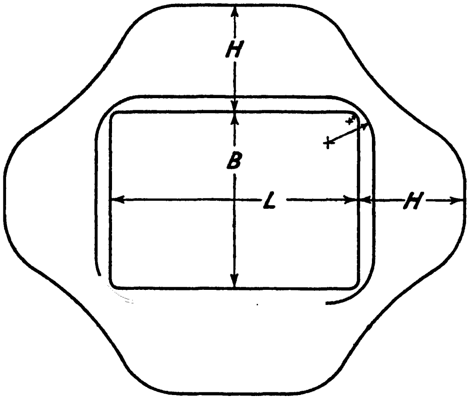

Fig. 12.18. Blank and stages for rectangular box

In modern practice it has been found economical to draw the metal during the first operation so that the corners are as near their final position as possible. The corner radii can then be redrawn in the second operation to about one-fifth of their value in the first, as in Fig. 12.18. The inner curve shows the ultimate plan of the box, the intermediate curve shows the plan of the first-stage pressing, and the outer curve shows the approximate shape of the original blank required, a shape that may be rather unexpected.

Along the straight sides of the box the dimension *H* is approximately the same as the ultimate depth required, because here the metal is simply bent during the drawing operation. At the corners, however, drawing proper occurs and the metal here is "fed" from either side, both in the initial draw and in the second operation when the corner radius is being reduced. Consequently the full depth of metal is not required in the blank, and if it were present its effects would be to produce unwanted "ears" at the corners, to increase the tendency for puckering, and to cause unduly high metal stresses in the corners near the base. Although empirical rules have been proposed to predetermine the proper shape of blank for rectangular pressings the exact shape has generally to be found by trial in each case, especially with irregular forms of pressing.

Forming. If the form required in a pressing is entirely convex it is usually possible to produce it by the ordinary process of drawing over a suitably shaped punch, and the function of the die is merely to provide a suitable throat through which the punch and sheet metal can pass. Sometimes the final product can only be obtained in its detailed form by pressing it between the punch and a die which mates with it over the whole or a considerable portion of its surface. Even when the final product has a convex profile it is found economical, at times, to draw it to a shape which only approximates to this profile, and to give it its exact form by a special final operation. The accurate shaping of a shell, already drawn as nearly as practicable to its final profile, is known as "forming".

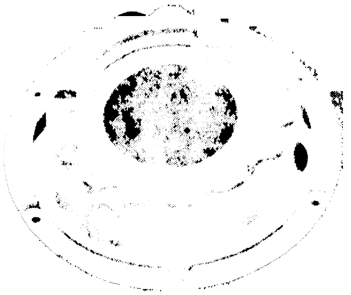

Fig. 12.19. A planished pressing (clutch case)

Planishing. Where concavities or marked changes in curvature are required, or where wrinkling is liable to occur, it is necessary to "planish" the pressing between the punch and a mating die. Since the operation of planishing involves metal to metal contact it clearly demands careful tool making and setting in order to ensure a sharp form without overstraining the press.

Embossing. Often the forming operation consists merely in the impression of details without any further deformation of the pressing as a whole, and it is then essentially an "embossing" process, making little demand on the plastic properties of the metal. At other times a more general straining of the metal is involved, though this straining is less severe than in a normal drawing operation. In either case the danger of tearing the metal is less than the danger of wrinkling. Consequently it is necessary to give careful attention to blank-holding control, and it is generally safer to apply *stretching* rather than compression in the forming process.

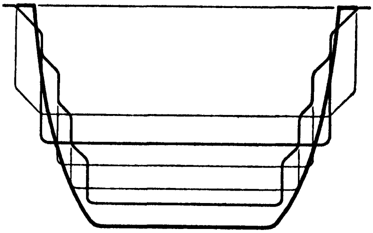

Fig. 12.20. Stepped drawing and forming

A good example of a combined forming and embossing operation is afforded by the clutch cover, Fig. 12.19. Fig. 12.20 shows an operation involving general strain, where a vessel of smooth and generally convex profile is formed from a stepped pressing produced in five drawing operations. The development of a vessel of this kind by successive stepped pressings is a common procedure which tends to reduce variations in wall thickness and to simplify tool design.

The penultimate shell is shaped so that the final forming is essentially a stretching operation, apart from a slight drawing at the rim. Owing to the sudden changes in curvature in the stepped shell it is necessary to use a planishing die in the final forming operation.

BULGING. The forming of a vessel in which the body is larger than the mouth involves either *bulging* or *necking*. Since bulging is essentially a stretching operation, while necking necessarily involves compression, the former is generally safer and is more generally adopted. Either operation may be carried out in a spinning machine or lathe, but bulging in particular is often effected in a press. For this it is necessary to provide a *split die* and some form of collapsible or elastic punch; metal punches of segmental construction are sometimes used, but these are elaborate and expensive and do not produce a perfectly circular product.

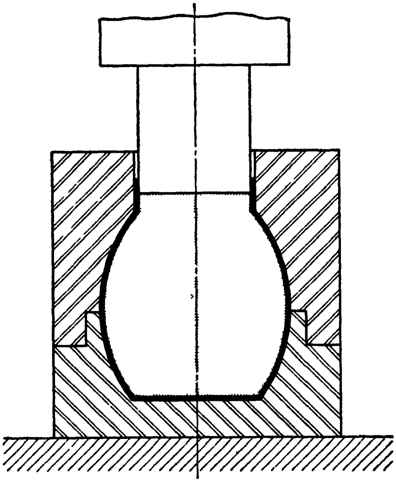

Fig. 12.21. Bulging with rubber punch

Better results are obtained by the use of a rubber-headed punch, after the manner indicated in Fig. 12.21. Here, the rubber head, which in the unstrained condition just enters the mouth of the vessel, expands when it reaches the base and exerts a high lateral pressure as the punch completes its working stroke, recovering its unstrained form as the punch is withdrawn. A variant on the rubber-punch technique is provided by *hydraulic* bulging. The vessel is filled with fluid, the punch head taking the form of a piston or ram which just fits the mouth of the vessel. The fluid exerts lateral pressure and forms the vessel as the punch moves in to compress it. With both rubber-punch and hydraulic bulging the exact form of the formed vessel is determined by the shape of the split die. The extent of bulging made possible by these methods is quite considerable, and an expansion of 30 per cent has been obtained in a single operation with suitable metal.

NECKING. The converse operation of necking, when carried out in the press, consists in forcing a suitably shaped partial die over the open end of the vessel; this operation is rather like pressure sinking but is more liable to cause buckling because of the absence of a closed end. A reduction of about 10 per cent per operation is representative of normal practice.

LOAD CONDITIONS

of Blanking and Deep Drawing Operations

By DR. F. KOENIGSBERGER

Blanking. The blanking force depends on the area a which has to be sheared and the shear resistance f_s of the material; or $P = a \times f_s$. The area a equals the product of the circumference of the component and the thickness t of the material. For a circular piece of diameter d the area is $a = \pi dt$ hence $P = \pi dtf_s$. If the permissible compressive stress f_c of the punch material is K times f_s, then the blanking force P, equal to πdtf_s, for blanking out a circular component, will not overstress the punch of the same diameter d provided πdtf_s does not exceed $(\pi d^2/4) \times f_c$, that is $(\pi d^2/4) \times kf_s$. Hence, t must not be greater than $d/4 \times k$ and d must not be less than $4t/k$.

The smallest diameter which can be blanked out of a sheet is equal to four times the sheet thickness divided by the ratio between compressive strength of the punch material and shear strength of the sheet material.

The blanking force is slightly affected by the clearance between punch and die (Fig. 12.22*), because the frictional resistance grows with decreasing clearance.

The driving gear of the press has to overcome the blanking resistance plus the frictional resistance exerted by the various parts of the mechanism in operation.

The actual blanking operation is usually carried out shortly before the press ram has reached the bottom position during its downward stroke (Fig. 12.23*a*). In order to determine the energy required to carry out the operation the force to be exerted on the ram can be plotted against the developed circle described by the crank (radius r) during one revolution (Fig. 12.23*b*). The frictional

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* See G. Schlesinger, *Die Werkzeugmaschinen* (Machine Tools), Springer, 1936.

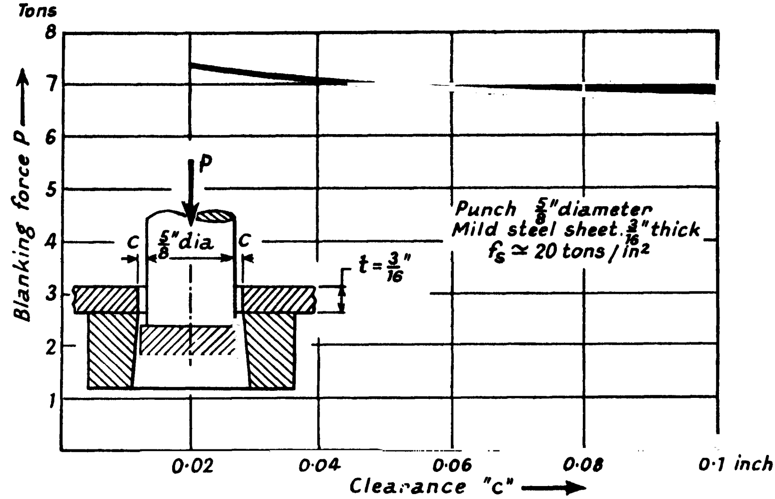

Fig. 12.22

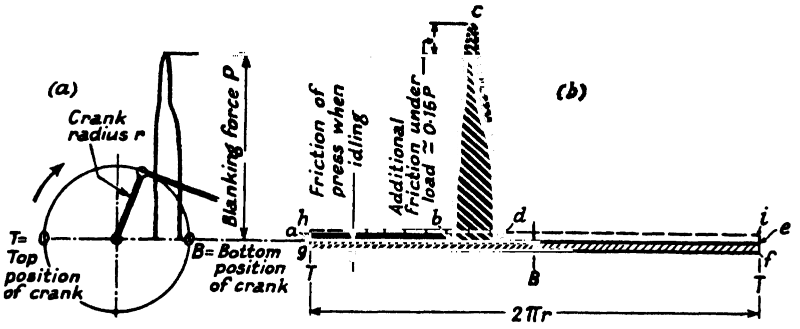
(a)
Crank radius r
T= Top position of crank
B= Bottom position of crank
Blanking force P
Friction of press when idling
Additional friction under load ≃ 0·16P
(b)
P₁
c
a
h
b
d
i
e
f
g
T
B
T
2πr

Fig. 12.23

resistance during idle running of the press can be assumed constant over the complete revolution, whilst the blanking force plus the additional friction due to the heavy loading of the bearings has to be applied over a very short portion of one revolution.

The total energy required for one complete revolution of the crank is represented by the area "a–b–c–d–e–f–g–a" where "b–c–d" represents the energy required for the actual blanking operation, which has to be taken out of the flywheel, and "a–e–f–g" the mechanical losses in the press during idle running. If a rectangle "a–h–i–e" is constructed with the same area as "b–c–d" then the total energy of one operation is represented by area "g–h–i–f". If the circumferential velocity of the centroid of the flywheel rim (mass m) is reduced from v_1 to v_2 during the blanking action, then the energy required is

$$U = \text{area "b–c–d"} = \text{area "a–h–i–e"} = \frac{m}{2}(v_1^2 - v_2^2)$$

$$v_2^2 = v_1^2 - \frac{2U}{m}$$

$$\frac{v_2}{v_1} = \sqrt{1 - \frac{2U}{mv_1^2}}$$

$$v_2 = v_1 \cdot \sqrt{1 - \frac{2U}{mv_1^2}}$$

$$\frac{v_1 - v_2}{v_1} = 1 - \sqrt{1 - \frac{2U}{mv_1^2}}$$

This reduction of the flywheel velocity during the blanking operation should be kept below 20% and is usually not less than 5%.

Deep Drawing. For the deep drawing operation (Fig. 12.24) the force on the punch P_d, the actual drawing force, and the force on the blank holder P_h, which holds the blank down and prevents puckering, have to be considered (see page 317). Furthermore, a certain force P_r is required (opposite in direction to P_d and P_h) for stripping the completed workpiece off the punch (Fig. 12.25*a*).

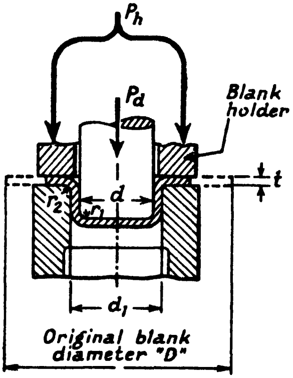

Fig. 12.24

Bad tool quality may considerably increase these forces. Fig. 12.25*b*[*] is the record of a drawing operation similar to that shown in Fig. 12.25*a*, but with a slightly tapered die which resulted in almost jamming the component at the bottom of the stroke.

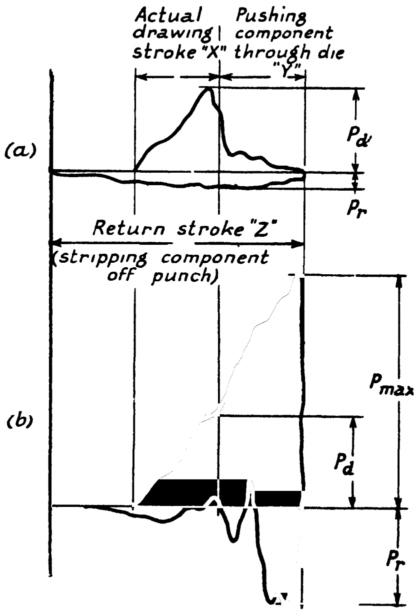

Fig. 12.25

The drawing force P_d can be estimated from the punch diameter d, the thickness t, the strength f of the workpiece material and a factor m which depends upon the drawing ratio D/d (see Fig. 12.24, also page 323), that is $P_d = dtmf$. The holding force P_h is usually estimated from

$$P = p\frac{\pi}{4}\cdot (D^2 - d^2)$$

where p, the specific pressure, varies between 150 and 400 lb./in.^{2}, the higher pressure being used for thinner material.

The influence of the radii r_1 of the punch and r_2 of the die has been described on page 324.

The clearance $(d_1 - d)/2$ between die and punch is important. It will be obvious that too small a clearance will result in a high drawing force, but even too large a clearance, unless it is out of all proportion, may cause a high force on punch and blank-holder. This is due to the greater tendency of the workpiece material to pucker. In the case of very large clearances, which do not resist puckering at all, the forces drop again. In Fig. 12.26* the forces on the punch (P_d) and the blank-holder (P_h) are shown, as measured during a particular drawing operation, for various clearances $(d_1 - d)/2$ in relation to the material thickness t.

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[*] From Ruhrmann: Thesis (T. H. Karlsruhe, 1925).

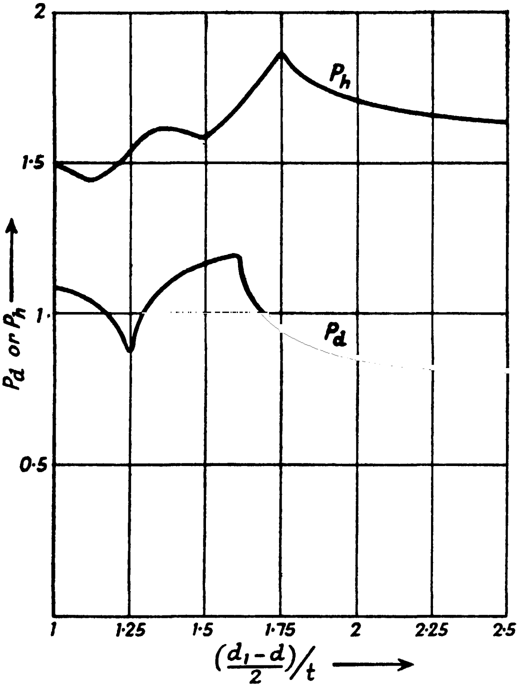

Fig. 12.26

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* From Goederitz: *Zeitschrift für Metallkunde* (1934).

For Bibliography see end of book.

CHAPTER XII

PRESSWORK

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Presswork in Principle. Presswork is a term which can be applied to a large variety of operations in connection with the fabrication of most metallic and some non-metallic articles. Parts may be made complete or by a series of operations, or the press may be used simply to add an embellishment. Among the types of presswork, *Blanking* implies cutting the outside contour; *Piercing* the cutting of holes of any shape or size inside the contour; *Perforating* the cutting of a large number of holes inside the contour; *Drawing* the reducing of the blank to the desired forms; *Bending* the simple forming of bends in one plane only; *Forming* the bending into complex shapes on more than one plane; *Coining* the surface deformation into fine detail by cold compression; *Embossing* a forming operation (limited in depth to about three thicknesses) and used for raising letters or designs on thin metal.

The terms *pressing* or *stamping* referred to in this chapter are general terms only, covering either the finished article or the manufacturing process, including those mentioned above.

The steps necessary to produce any finished pressing are planned in sequence, each requiring a separate set of tools for insertion in the press. Generally, the tools or dies make only the part for which they are designed, the exception being the simple bending operations carried out on a brake press where the tools are made up from simple shapes to do as many operations as possible, and remain in the press for long periods.

The ideal, for overall efficiency, is to maintain all presses and tools in a sequence in continuous operation, the speed being conditioned by the slowest, although the blanking-press operation for instance might be capable of twice that speed. It is not desirable, however, to run it faster, as it would simply create a stock-pile of material and lower the efficiency of the press shop because of the extra handling involved.

The types of article which can be made on a press range from the small flat blank to a large one-piece roof panel of an all-steel saloon car. Sheet-metal fabrications such as car-body structures are required in large quantities—sometimes over one million—and are made by welding together a series of pressings. There is an optimum size for both press and tools, depending upon the relationship between the cost of large stampings and the cost of putting together smaller stampings, combined with the availability of the raw material in certain sizes. It is of interest to note that the strength and rigidity of the car-body structures is gained, not so much from the latent strength of the material, as from the shapes and sections welded together. By careful design the maximum rigidity, which is usually the prime consideration, can be achieved with minimum weight and cost.

Presswork, like other methods of manufacture, inevitably produces a certain amount of scrap material, e.g. the blanking of irregular shapes from a strip leaves a framework for disposal; double-action forming leaves all the blank-holder draw beads to be sheared off, and of course the punchings from pierced holes are innumerable. It is normal practice to design both tools and parts to produce the minimum of scrap, and where large pieces of material are scrap from one operation they should be used as raw material for smaller parts.

Presswork Mechanics. Before dealing with press design, it is advisable to discuss certain fundamental requirements. These fall into two convenient groups which it is important to distinguish in relation to press and article design. On the one hand are the vast majority of stampings made in sheet metal and of constant thickness throughout; on the other, those produced from a slug or billet and continuously pressed or ironed to the shape required; this could be described as cold forging.

An example from the first group would be any motor-car body panel; these require a low pressure while the metal is carried by the punch into the recesses of the forming tools, with the maximum pressure at the end of the stroke to ensure perfect formation over the die shapes, a requirement met by the crank press. In the second group are such items as shell-cases which receive their final form as the result of a series of operations, starting with a circular billet of thick material, each contributing towards the final shaping and reduction of thickness. The billet deformation requires a constant pressure behind the dies and this requirement is met by either a rack-and-pinion press or a hydraulic press.

To determine the pressure exerted by a crank press at points above the bottom dead centre, one may use the formula

$$P = C^3/(sd - d^2)$$

where P = pressure exerted (in tons), s = stroke (in.), d = distance from bottom of stroke (in.) and C = diameter of crank journals (in.). Reference can also be made to the press manufacturer's chart.

A practical formula for determining the pressure required to blank a given shape on a crank press is:

P = Length of Periphery × Thickness × Shear strength of material.

The blanking pressure is the maximum required, since it will shear the material. All other operations would be done at lower pressures. On the analysis of load conditions, see later in this chapter.

A large variety of presses is available, from the simple hand-operated flypress attached to a bench, to the large specialized power-operated double-action and triple-action machines for large automobile panels. The choice of a press depends upon the size of article required and the type of the operations required to produce it. In view of the capital expenditure necessary for new presses, the tool designer will almost invariably design his tools and plan the operations to suit machines already installed. For example, a large roof or body side-panel may be made in two or more pieces, enabling smaller sheet-metal blanks, and smaller presses, to be utilized.

In principle, however, all the mechanical presses are similar in operation and vary only in individual style and arrangement. Except in the simplest hand presses which operate by means of screws, and the rack press which is operated through a gearbox, the force in a mechanical press is derived from the kinetic energy developed by the flywheel and transmitted through a crank and slide. In a typical modern press shop for automobile stamping work presses of 12, 30, 90, 120, 150, 450, 900 and 1,500 tons will be found—normally the upper limit, though presses can be made to much higher tonnages—one hydraulic press near Los Angeles has a stated tonnage of 8,000, and is used for large aircraft panels.

Depending on the type of press, the number of strokes per minute can range from 3½, 7, 12, 24, 35 up to 100. A highly important feature of any press is the work opening or "daylight".

This governs the size of tool which can be inserted and ranges from a few inches on the smaller presses to six or seven feet on the largest.

The force in a mechanical press is normally transmitted by the crank slide from a flywheel, connected directly to the crankshaft or indirectly through gears. Since the kinetic energy of a flywheel is proportional to the square of its speed it is often advantageous, when using gears, to use a slightly smaller flywheel and run it at a higher speed. A geared press will maintain its pressure on the slide through a greater proportion of its stroke, a desirable feature for many types of stamping.

When a hydraulic or air cushion, or a rubber buffer or spring device is fitted to a press to hold the blank, the total horsepower needed is more than that required to drive the press alone. The proportion of the blank-holding pressure to the pressure required to form the article may be 20 per cent. Thus on a press frame designed for a pressure of 100 tons near the bottom of the stroke, a blank-holding pressure of 20 tons would be used. A motor of suitable horse power must, therefore, be provided to cater for both forming and blank-holding pressures.

Single-action presses with one slide only are driven by a crankshaft having one or two connecting-rods (two being used to prevent tilting of the dies and to reduce the load on the guides) and connected through a clutch to a flywheel, either direct or through single, double or triple gearing. This type of machine is generally preferred for shallow draws and irregular shapes. Some of these presses will have two crankshafts, each with two cranks and two connecting-rods, making what is known as a four-point connection, in which all four corners of the slide are suspended. This gives a more even pressure on the work.

Double-action presses have two slides, an inner and an outer. The inner slide is actuated by a crank and connecting-rod, as in a single-action press, and operates the forming punch; the outer actuates the blank-holding mechanism and is driven by cams which act either on pressure rollers, running in oil baths, mounted on opposite sides of the outer slide, or through a system of toggle levers. The toggle mechanism is used on all the larger presses. Its chief characteristic is that the full pressure on the blank is carried by the solid frame of the machine and not by the shaft carrying the driving cams. The cams have a constant radius for about a quarter of a revolution, thereby ensuring a uniform pressure on the blank while the forming punch on the inner slide does its work.

There are also, for special purposes, triple-action presses in which three separate but co-ordinated operations are carried out at each descent of the ram.

Accessibility of the tools is always important, and where it is a prime factor the open C-type of press frame, either vertical or inclined, is preferred. The press is fed and operated from either side or from the front. A special feature of the inclinable press is that the angle of inclination may be adjusted from the vertical to facilitate rapid removal of the finished stamping. The limitation on the open C-type press frame is the load which can be carried, and for the higher tonnages the closed press frame is used, accessible only from the sides. Angular alignment under load between punch and die will be more accurate with the closed frame than with the open C-type, since the frame is symmetrical and displacement of the press head will be parallel to the work.

Some Typical Machines. In most workshops many different types of press will be found, some purely mechanical, others hydraulic, and either general-purpose or specialized. The following descriptions cover a typical range.

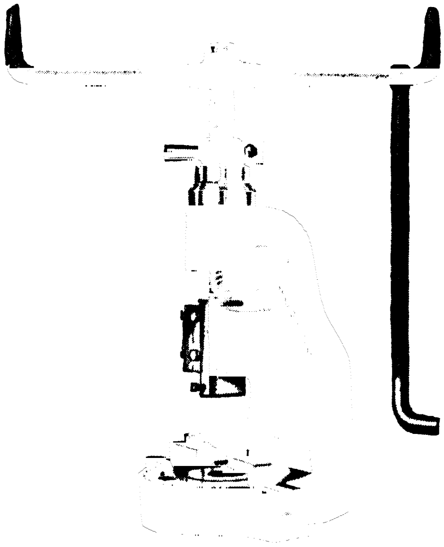


Fig. 13.1. Standard hand-operated press

(T. Norton & Co. Ltd.)

1. *Hand Press.* Fig. 13.1 shows a standard hand-operated machine, also known as a flypress. This type, when operated by

hand, is usually mounted on a bench or stand and is suitable for small blanking, forming and piercing operations where the pressure required is light. The operator grasps the handle (shown hanging vertically) and the action of swinging it round turns the screw thread and moves the tool up and down. Additional pressure is generated when required by the attachment of a ball weight to the spikes over the handle, thus producing the effect of a flywheel. The press illustrated is No. 6 in a range of ten sizes. In a small press shop it would be usual to arrange them in groups, or linked to suit the job in hand. In the larger shops where all sizes of press are available the hand press is used for minor operations on large stampings and will be set up between the larger presses.

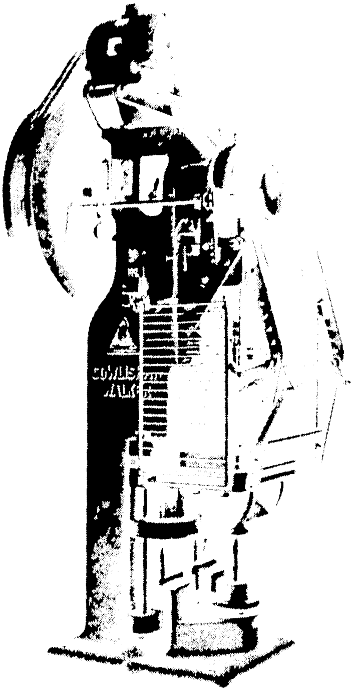


Fig. 13.2. Single-action open-fronted wheel press
(*Cowlishaw Walker & Co. Ltd.*)

2. *Single-action Press.* Fig. 13.2 shows a single-action open-fronted wheel press, ungeared, and for pressures up to 30 tons. The stroke is 3½ in. and 100 strokes are made per minute. The flywheel

is mounted at the rear and connects with an eccentric or cam to give a direct drive through the clutch. Stampings requiring pressures up to 60 tons can be made on the press shown in Fig. 13.3. This is a general-purpose open-fronted, geared machine, operating with a stroke of 7 in. at 40 strokes per minute.

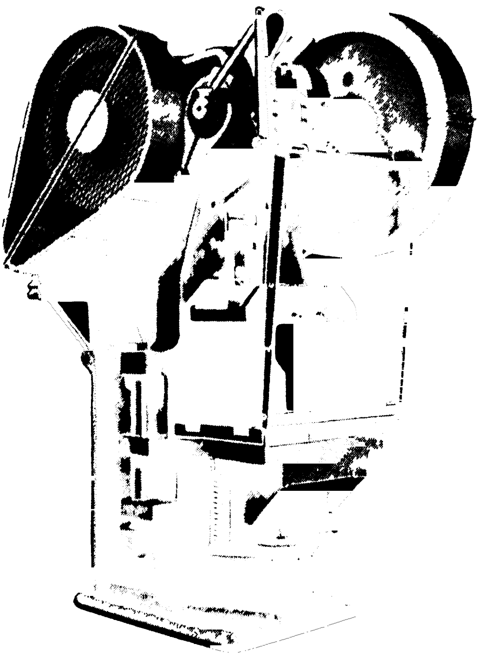


Fig. 13.3. Open-fronted multi-purpose press—60 tons
(*Cowlishaw Walker & Co Ltd*)

Where it is desired to let the work fall through the back of the machine, an inclinable press is used.

Many large stampings requiring only single-action tools but much higher tonnage, are made on the double-side double-crank press, Fig. 13.4. A press of this type has a capacity of 400 tons, a stroke of 16 in. and a speed of 14 strokes per minute.

3. *Double-action Press.* Where the design of the stamping is such that a separate blank-holder and punch are necessary, a double-action press is used. The punch is attached by a connecting-rod to the crankshaft; the blank-holder slides separately but in relation to the punch movement. Thus the blank-holder is lowered on to the

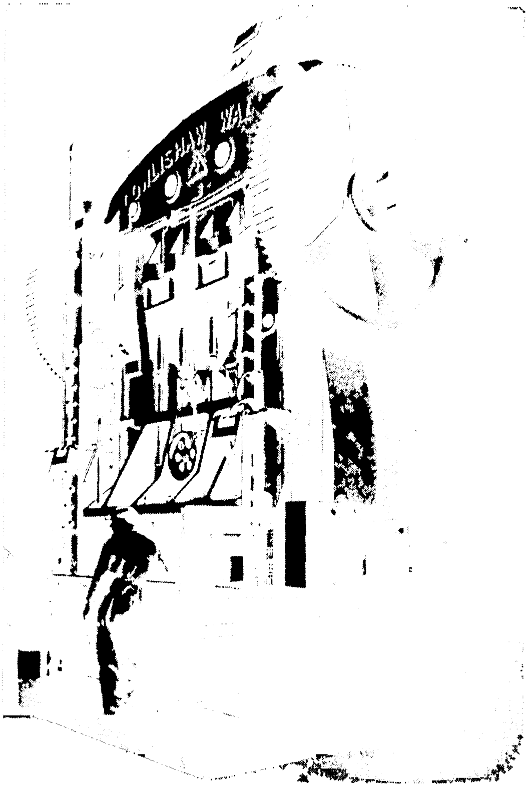


Fig. 13.4. Single-action double-sided double-crank press—400 tons
(*Cowlınshaw Walker & Co. Ltd.*)

workpiece and dwells at the bottom of its stroke while the punch, carried by the inner slide, is forming the stamping. One of the largest of such double-action presses has a total capacity of 925 tons, with an inner slide stroke of 37 in. and an outer slide for the blank-holder of 26 in. The working area for the dies is approximately 12 ft. long by 7 ft. wide and this will accommodate some of the largest panels, including a complete car body side.

4. *Bending Press.* Bending or brake presses are widely used for operations on large plates. They provide a means of control by "brake" whereby the operator can stop the movement of the tool instantly and if necessary "inch" the slide forward by small

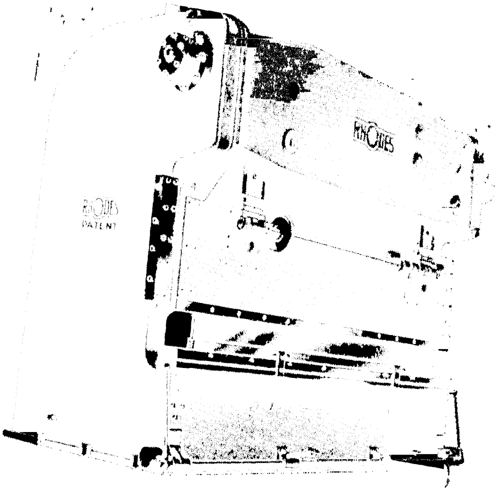
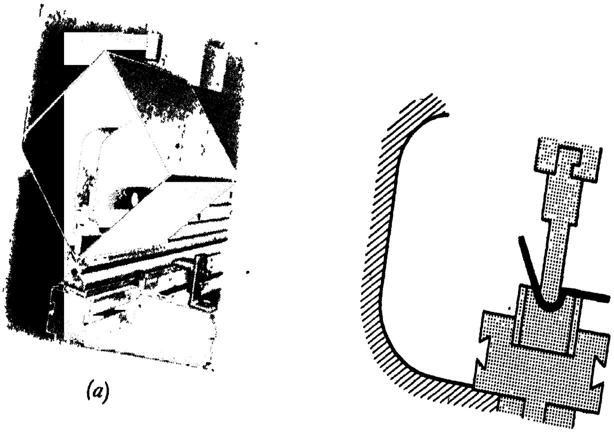


Fig. 13.5. Bending press or press brake; height 10 ft.
(*Joseph Rhodes & Son*)



(*a*)

Fig. 13.6

(*b*)

degrees. Fig. 13.5 is a modern fluid-driven machine which will accept sheet steel plates up to 12 ft. in length. With ingenious tool design, a large variety of angles and other forms can be produced. Fig. 13.6*a* shows an end view of a press brake with a tool in position—the simplest and fundamental vee-tool for producing angle bends. For general use, a male die of 85° and a vee-die of 85° are used and it is important to note that the dies touch the metal being formed only at the point of the vee and the edges of the die opening. The die opening to allow for this condition is approximately eight times the thickness of the metal. Fig. 13.6*b* shows the forming top tool and die for a particular round and sharp combination moulding.

Choosing the right Machine. As mentioned earlier, the tool designer may have a range of presses already installed, or alternatively a number of general-purpose machines. The choice of a press for a particular job is largely dependent on the following factors, which also influence the design of the press tools.

1. The distance above the bottom of the stroke at which the pressure is to be first applied.
2. The length of stroke required. When using a single-action press, the stroke should be $2\frac{1}{2}$ times the depth of the article.
3. The size and type of die required.
4. The amount of pressure required to operate ancillary attachments when forming the pressing.
5. The size of the sheet blank or article and the method and direction of progress through the machine.
6. The position of the machine in the production line; there may be special consideration for combined or multi-operation tools in a single-action press.

Cold Pressing. Most pressings are made from light-gauge metals and can therefore be processed at room temperatures. In this category will be found all the steel, aluminium and other non-ferrous alloy pressings used in motor-car body work, refrigerators and many domestic articles, using metal of 22 to 10 gauge.

The material in most use at the present time is mild steel. The type normally used has a tensile strength of 18–20 $t/\text{in.}^2$ and is relatively soft and ductile. After cold working on the press, the tensile strength may increase up to 25 $t/\text{in.}^2$. Stampings can also be produced cold from $\frac{1}{4}$ in. thick nickel steel for chassis frames or even $\frac{3}{16}$ in. thick for mine hemispheres, but above this thickness the tonnage required is so high that it becomes more economical to use another technique (hot pressing).

It should be noted that always, to obtain satisfactory presswork, the material is bought according to the pressing characteristics and the final finish required, and not to any given standard composition. Modern sheet and strip mills are producing sheet and coiled steel in large quantities to a range of mechanical properties which in general suit most stamping requirements. The choice of material for a given job is a matter for discussion between the pressing company and the supplier. The reader will appreciate from the preceding chapter and from that on *Steel Sheet and Strip*, in Part I of this work, that a number of complex metallurgical factors are involved in drawing operations and it is best for the material-supplier to understand fully the conditions set up by the press tools in each case.

Press Tools and Operation. In production, except for the simplest of parts, it is not generally possible to complete the article in one operation, and several may be necessary, and where there is extreme depth, several successive draws are required. The tool planner, therefore, has to plan a sequence of operations to produce each part, with an indication of the type of press to be used for each. Often, they are combined in one tool, e.g. blank and pierce, and it is possible also to assemble several small tools in one large press, provided the stroke is the same, thus using one press stroke for several tools. Much thought is now concentrated on the mechanical combination of a line of presses so that a stamping is progressed from one operation to another until completed, thus saving storage and trucking.

Except where permanently linked to a production assembly line, the press tools are removed from the press at the end of a run of stampings, and are stored. A new set of tools for another part is then immediately installed. Press runs are usually made for 500 to 3,000 or even to 30,000 items, giving several weeks' stock.

When tools are complete and ready for work they are put into a production press and carefully adjusted by the die-setters. This die-setting—not to be confused with die-fitting—is not a complicated process but does require a certain amount of time, depending on the size of the die. Small dies can be lifted by hand, others are lifted from the die park on fork-lift or power trucks and the larger dies weighing many tons are manoeuvred by a crane, using a cable through an eye-bolt in the floor. When the dies are in position, the die-setters will run a few trial stampings before releasing the job for production. The press is idle during die-setting and every effort is made to reduce this time to a minimum.

Tooling Considerations. Certain alternative methods of tooling can be adopted and must be carefully studied by the tool planner to ensure that each press is used to the maximum advantage.

First, double-action *drawing* must be considered against single-action *raising*. Double-action drawing presses possess the following advantages: (*a*) They are better for balanced shapes and deep draws over approximately 6 in. (*b*) The blank-holder pressure is transferred to the press frame through the toggle levers, leaving the full power of the crankshaft for the forming operation, with the advantage that there is no sudden extra load at one point in the stroke. (*c*) A smaller double-action press will do work equal to a larger single-action press and will use less power and less-expensive tools. (*d*) It is possible to draw straight through the tools if desired, since the sides are clear.

Single-action presses with raising equipment have these advantages: (*e*) With short strokes up to 18 in. they can be run some 25 per cent faster than double-action machines, where the stroke is often 36 in. or longer. (*f*) They are preferable when heavy-forming or embossing operations are required at the bottom of the stroke because the crankshafts have better support than is possible in a double-action press. (*g*) They have a wide use and can be employed for blanking, forming, etc. with equal efficiency.

Second, it is useful to keep in mind the various means of feeding the press with raw material or blanks. Mechanization here, formerly limited to the smaller presses, is now applied to the largest, with roller conveyors, mechanical hands etc. between the rows of machines. It is not impossible to introduce an automatic welding operation, when required, between press operations, provided the output is sufficient to justify the expenditure on the equipment.

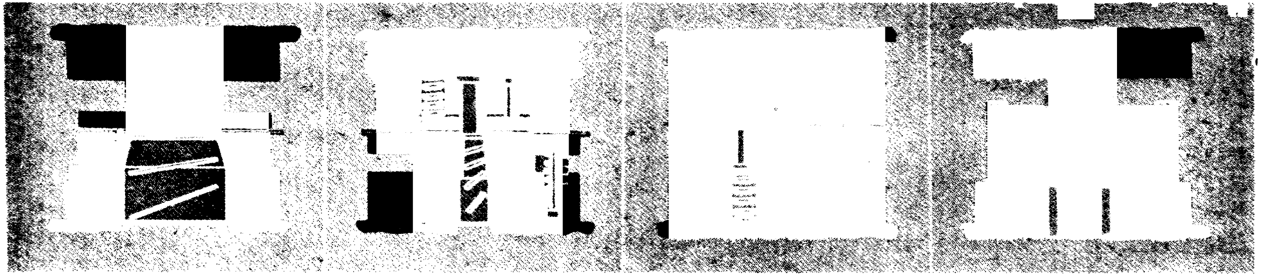
Some Typical Tools. Starting with the tools for the smaller presses, Fig. 13.7, is a series of six diagrams showing typical tool designs for the following operations:

1. Blanking: the strip of metal is fed under a fixed stripper and the blanks, when cut, fall through and are collected below the tool.

2. Combined Blank and Pierce: the blanking die incorporates a punch and only the punchings fall through the lower part of the tool. Blanking and piercing are done together with one stroke of the press.

3. Embossing: the dies produce the crinkled shape according to the pattern required and the stamping is pushed loose from the lower die by the spring ejector.

4. Raising: the dies produce the channel section from the

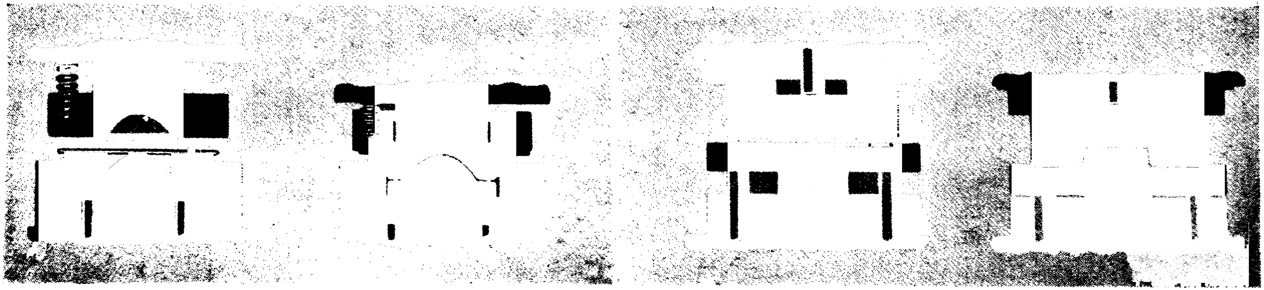


BLANK
Shown with fixed stripper. Pilots should be incorporated in the tools

BLANK & PIERCE
Shown with spring stripper and ejector. Pilots should be incorporated in tools

EMBOSS
Shown with spring ejector

RAISE
Shown with air-cushion ejector

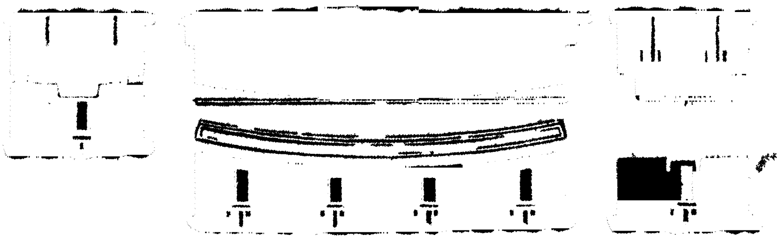


Stroke up BLANK & DRAW Stroke Down
Shown with air-cushion pressure pins and spring top stripper. Pilots should be incorporated in tools

Stroke up DRAW Stroke down
Shown with air-cushion pressure pins and positive top knock-out

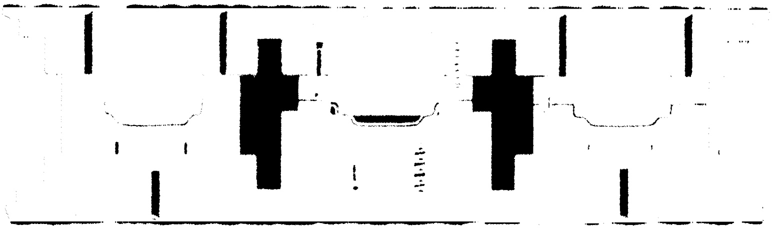
Fig. 13.7

(*Wilkins & Mitchell Ltd.*)



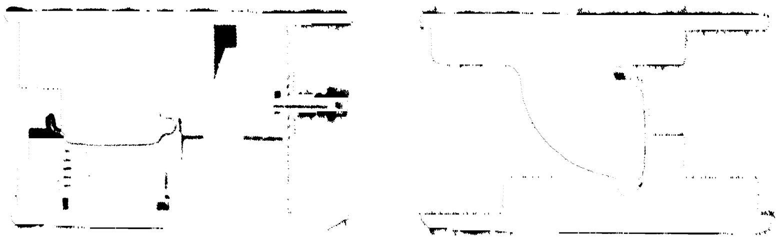
Stroke up FORM Stroke down

Shown with air-cushion pressure pins and positive top knock-out



DRAW TRIM RE-DRAW

Shown side by side on common plate, embodying air-cushion and spring pressure pins and positive and spring top knock-outs Plate should be incorporated in centre tool STROKE DOWN



EDGE TURNING

Overhung Tool—Stroke down

EDGE TURNING

Side Action—Stroke down. Shown with spring-loaded pressure plate

Fig. 13 8 (*Wilkins & Mitchell Ltd.*)

blank and the lower die incorporates an ejector operated by an air cylinder.

5. Combined Blank and Draw: the blank is cut by the upper die on a lower die supported by an air cylinder and when fully depressed the shape is formed.

6. Drawing: the blank is controlled by the outer parts of the dies while the inner punch fixed to the lower die forms the shape.

The diagrams illustrated in Fig. 13.8 show a further range of operations, and methods of installation in the larger presses, as follows:

7. Forming: the simple die shown in front and end elevations is for stamping the channel section, the outer part of the lower die operating an air cylinder.

8. Progressive Tooling: the press is fitted with three separate tools, all using the same length of stroke. The stamping is progressed by the operator, from the draw die to the trim die and thence to the re-draw die, between each stroke of the press.

Fig. 13.9. Double-action tool for roof panel

(Pressed Steel Co. Ltd, Cowley, Oxford)

9. Edge Turning: the flange on the stamping shown in stage (8) is being turned by direct action.

10. Edge Turning: an alternative method of turning the flange by indirect action, typical of a cam die.

For large stampings the tools and presses are on a much greater scale, as illustrated in Fig. 13.9, which shows a 900-ton double-action press fitted with the dies for the first forming operation on a one-piece roof panel. A flat blank of steel approximately 0·040 in. thick, already sheared to shape, is placed in the die and is removed when completely formed. The behaviour of the double action is such that the outer part (blank-holder) is lowered to grip and control the steel by means of the draw beads—visible in the picture—and stays down while the inner punch forms the depths of the stamping. During this operation the press guards—not shown—protect the operators.

Stampings. One of the largest steel panels produced for motor-body work, a floor panel, illustrated in Fig. 13.10, is produced from

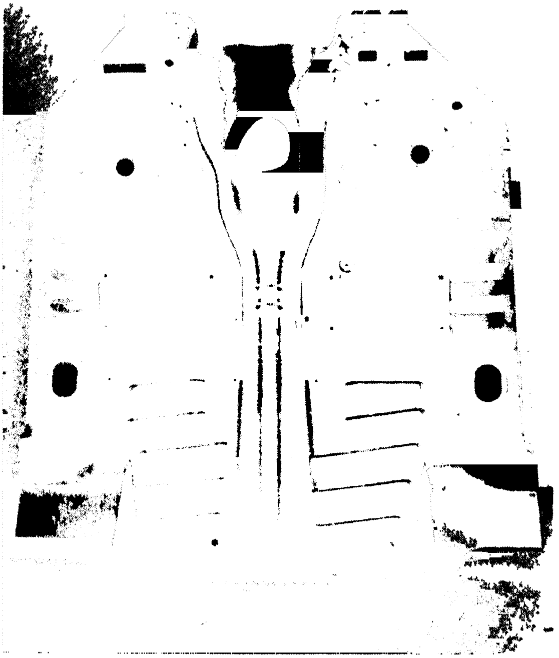


Fig. 13.10. Floor panel for car body, about 5 ft. square

(*Pressed Steel Co. Ltd., Cowley, Oxford*) steel approximately 0·048 in. thick and incorporates the toeboards, propeller shaft tunnel, gear-box cover, jacking holes, seat-supports, all in the same pressing from one flat sheet, with stiffening depressions and swages. The panel is shown completed and ready for assembly by spotwelding into the car body-structure. Since this is an interior part, no special finish is required and it would require only deep-drawing-quality steel (open-hearth single-pickle deep-drawing oiled steel).

Where a surface finish of high degree, coupled with intricate design is required, a material with "automobile finish" is used; its specification would be "open-hearth single-pickle auto-body extra-deep drawing, oiled sheet steel.

Lubricants for Cold Pressing. To avoid close metallic contact between the dies and the metal to be formed, a lubricating medium is necessary. This avoids damage by scoring, prevents sticking to the die after forming, and generally eases the metal through the tools, since some drawing or forming operations involve considerable deformation and high friction forces, as in cold pressing.

Lubricating compounds must, therefore, be designed with high film strength to prevent removal by the wiping action of the tools on the metal. Film strength can be increased by the addition to the base oil of sulphur or chlorine compounds, and certain pigments or solid fillers, such as chalk, talc, etc. Metallic soaps such as calcium oleate may also be added.

Some degree of lubrication is necessary all over the metal being formed, and the normal protective oil on the sheet may be quite sufficient for this purpose. It is frequently desirable, however, to apply a drawing compound locally to assist control of the metal movement. Each operation must be studied with this in mind.

The design and selection of compounds aims at making them (*a*) non-corrosive, i.e. they must not stain or pit the dies or work either by direct oxidation or by chemical reaction; (*b*) uniform and stable in face of changes of temperature and humidity, and of dilution; (*c*) free from harmful fumes or smell, and requiring no toxic agents for their removal; (*d*) easily removed—important for economy. With pressed articles which have to be subsequently electro-plated or vitreous enamelled, a good press lubricant such as a calcium oleate may prove less desirable than one more easily removed.

In some comparatively heavy cold-forming operations, such as tube drawing, smoothing the walls of a metal cup, and cold extrusion, even the high film-strength of the metallic soaps when compounded has proved insufficient to prevent tool-to-metal contact. With steel, treating the blanks in a phosphating solution before applying the compound appears to provide a strong barrier between the sliding metal surfaces and prevents "pick up".

The use of a drawing compound must be considered in relation to tool cost and maintenance. Its value, apart from whether it is necessary to obtain the required quality of stamping, is a function of tool and die life, the total number of stampings required, and the power consumption on the press.

The compound, when required, is usually applied to the metal sheet with a brush immediately prior to the forming operation, but whenever possible, and particularly on mechanical press lines, an automatic spray should be arranged. The general subject of lubrication is treated in a later chapter.

Hot Pressing. Under this heading may be considered two variations: (1) where the metal to be formed must be softened and (2) where the tools are heated to maintain a certain temperature for a given time, e.g. during the curing of plastic materials.

In the first, the technique is obviously similar to forging. The die is lowered quickly on to the hot billet or bar and "forges" it to the shape required. To avoid sudden and premature cooling, the die surface can be heated by gas-flame torches. The hot pressing is carried out with one stroke of the press, and crank presses similar in principle to those previously described can be used, with special attachments. Articles weighing 6, 16 and 30 ounces would need pressures of approximately 60, 100 and 200 tons respectively, according to shape. A 100 -ton press could be used for a wide range of work. In addition, friction-screw presses can be used, since these are designed to give a quick stroke, operating through two high-speed flywheels. The edge of a friction disc connected to the screw is brought into contact with the side of one flywheel rim for the down stroke, and with the other, on the opposite side, for the upward stroke. A control linkage is arranged to rest the screw automatically at the top, until required again for the next stroke.

In the second variation, where certain non-metallic materials are involved, the tools or dies are required to remain closed for a period while the material cools or polymerizes (curing time). This involves a dwell period, and the clutch on a crank press must be designed to stop the die motion both at the top and at the bottom of the stroke. The general trend here is towards the electrically-controlled, hydraulic press, with a simple reciprocating motion.

Hydraulic presses of approximately 200 tons total capacity are now in operation using steam-heated matched-metal dies for reinforced plastic panels. The material is usually glass fibre and polyester resin, which cures in about four minutes while still in the press. The student requiring further information on this technique is referred to the ever-increasing literature.

For Bibliography see end of book.

CHAPTER XIV

MEASUREMENT STANDARDS AND EQUIPMENT

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IN this chapter basic standards of length are described, together with various standards of length and angle which are used in industry. The more common types of measuring equipment used in conjunction with these industrial standards are also described; such equipment will be found in a modern tool or inspection room.

National Standards of Length. The units in which linear measurements are made depend on one or the other of two basic standards, the Imperial Standard Yard (an arbitrary measure) or the International Prototype Metre (which was originally related to the circumference of the earth). The *Imperial Standard yard* is a bar of copper-tin-zinc alloy (16 : 2½ : 1), deposited at the Board of Trade in London. At each end is a hole containing a polished gold stud with three transverse lines ruled on its head, the head being sunk so that it lies in the neutral plane of the bar and thus any change in distance between the lines due to flexure of the bar is minimized. The yard is defined in the Weights and Measures Act of 1878 as the length between the central lines on the gold studs at a temperature of 62° F. when the bar is supported in a specified way.

The *International Prototype Metre* is a platino-iridium bar kept in Paris, having a cross-section of modified H-shape, the top of the cross-member lying in the neutral plane. The metre is defined as the distance at 0° C. between two transverse lines near its end. Accurate copies are possessed by the principal standards authorities throughout the world.

It will be noted that the length of the Imperial Standard Yard is defined at a temperature of 62° F., whereas ' length of the International Prototype Metre is defined at a temperature of 0° C. (32° F.). About twenty years ago international agreement was reached that the lengths of commercial standards should be at their nominal value at a common temperature of 68° F. (20° C.), an everyday temperature that may conveniently be maintained in any standards room.

Altogether, over the last fifty years, three separate determinations have been made of the ratio of the Imperial Standard Yard to the International Prototype Metre, and the accepted value for scientific purposes of conversion is

$$1 \text{ metre} = 39{\cdot}370147 \text{ in.}^*$$
$$\text{therefore } 1 \text{ in.} = 25{\cdot}399956 \text{ mm.}$$

For all practical purposes it will be seen that the usual conversion factor of 1 in. = 25·4 mm. has a very high degree of accuracy.

Material standards, such as the national standards described, have the disadvantage that any changes in their physical state which occur with the passage of time may affect their dimensions. It appears probable that, some day, national standards of length may be expressed in terms of a physical constant, such as the wavelength of a suitable monochromatic light. A method of measuring slip-gauges in terms of the wavelength of light, by using the principle of interferometry, is already in fairly common use.

Commercial End Standards of Length. The standards of length already described are known as line standards, as their lengths are defined by the distances between two parallel lines engraved on the standards. Commercial line standards have the disadvantage that there is a limit to the accuracy with which the lines can be produced, and that their employment involves the use of microscopes and other special equipment. For these reasons end standards have almost entirely supplanted line standards in modern industrial measurement. They are usually in bar or block form, having a standard length between the end faces which are finished accurately flat and parallel to each other.

In engineering practice the units of length defined by national standards are inconveniently large, and it is usual to use smaller units such as inches or millimetres.

End standards of length as used in industry are of two types—*slip-gauges*, and *length bars.*

SLIP-GAUGES. These gauges, first introduced by C. E. Johansson about fifty years ago, are of rectangular form, and are made of a high-grade steel, hardened throughout and then stabilized by means of a suitable heat treatment. The measuring faces have a lapped finish, and are made flat and parallel to one another with high accuracy. In the British Standard for slip-gauges, B.S. 888 : 1949, four grades of accuracy are specified, namely, *Workshop* grade, *Inspection* grade, *Calibration* grade, and *Reference* grade. The names Workshop and Inspection grades are self-explanatory; the Calibration and Reference grades, which are of the highest accuracy, are for use in standards rooms to check workshop and inspection slip-gauges. B.S. 888 : 1949, specifies allowable errors in the length between the measuring faces and also allowable errors in the flatness and parallelism of these faces.

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* "A Discussion on Units and Standards", *Proc. Royal Society A.*, **86**, 1005 (9 July 1946).

TABLE 14.1. ACCURACIES FOR SLIP-GAUGES

Unit = 1 *millionth of an inch*

	Workshop Grade			*Inspection Grade*			*Calibration Grade*			*Reference Grade*		
Size of Gauge	*Flatness*	*Parallelism*	*Length*	*Flatness*	*Parallelism*	*Length*	*Flatness*	*Parallelism*	*Length*	*Flatness*	*Parallelism*	*Length*
Up to and including 1 in. (25 mm.) .	10	10	+10 -5	5	5	+7 -3	3	3	±5	3	3	±2

It is uneconomical to have slip-gauges made individually to all sizes of standard that are likely to be required, and they are normally supplied in carefully selected sets, the size of any required standard being made up by combining suitable slip-gauges. It is surprising how few slip-gauges are required in a set to provide for an enormous range of sizes. One popular set comprises 81 pieces; the sizes of the individual slip-gauges being given below:

SET No. E81

Range (*in.*)	*Steps* (*in.*)	*Pieces*
0·1001 to 0·1009	0·0001	9
0·101 to 0·149	0·001	49
0·05 to 0·95	0·05	19
1, 2, 3, 4	1	4
	Total =	81

By the use of this set end standards can be built up covering measurements from 0·2000 in. upwards by 0·0001 in. steps. For example, an end standard of 4·1809 in. may be obtained by building up the following gauges:

$$\begin{array}{rl} & 0{\cdot}1009 \\ & 0{\cdot}130 \\ & 0{\cdot}95 \\ & \underline{3{\cdot}00} \\ \text{Sum} & \underline{4{\cdot}1809}\ \text{in.} \end{array}$$

Wringing. If two slip-gauges are simultaneously pressed and slid together on their measuring faces they will adhere firmly and are said to wring together. A wringing action can only be obtained if the contacting faces are clean and very accurately flat; it is improved by very slight traces of a suitable lubricant, but too much will prevent wringing. It appears probable that the action of wringing is due to some form of ***intermolecular attraction*** between the slip-gauges. The advantages in the building up of end standards are considerable, as it is possible to handle a built-up standard of four or five slip-gauges as one without any necessity to clamp them together. The effect of the thickness of the film of lubricant on the size of the slip-gauge combination is negligible for practical purposes; tests carried out at the National Physical Laboratory indicate that the actual wringing film amounts only to about one five-millionth of an inch. Slip-gauge combinations are suitable for providing end standards up to about six inches in length, but above this size they are difficult to handle, and length bars used in conjunction with slip-gauges are to be preferred.

LENGTH BARS are made of high-grade steel, hardened at the ends only and then stabilized by a suitable heat treatment. They are of circular section, about $\frac{7}{8}$ in. diameter, and have their end faces finished accurately flat and parallel.

The British Standard for Length Bars, B.S. 1790: 1952, specifies three grades of accuracy, namely Workshop, Inspection and Reference grades, corresponding to the equivalent grades of slip-gauges. Workshop grade bars are provided with tapped holes at the ends so that they may be joined together by screwed studs, thus providing a rigid assembly. The changes in length produced by the effect of the screwed joints may be neglected for most purposes for which Workshop grade bars are intended to be used. These changes in length are, however, of sufficient importance to render undesirable the use on Inspection and Reference grade bars of screwed joints of the type recommended in B.S. 1790 : 1952 for Workshop grade bars. For this reason the ends of Inspection and Reference grade bars are left plain.

If a length bar is used in a horizontal position and is mounted on two supports then the sag caused by its own weight will have the effect of reducing the overall length between the end faces. If the bar is supported at two symmetrically placed points, termed the "Airy points", spaced apart by 0·577 of the length of the bar, then this sag is reduced almost to a minimum and the ends of the bar are brought parallel. It is recommended, therefore, that when used in a horizontal position, all bars of lengths 6 inches and above shall be supported at the "Airy points". The positions of the "Airy points" are indicated on Workshop grade bars by means of scribed lines and on Inspection and Reference grade bars by means of raised bands about $\frac{1}{4}$ inch wide.

The lengths of the Workshop grade bars range from $\frac{1}{2}$ inch upwards, and of the Inspection and Reference grade bars from 1 inch upwards. The lengths are in multiples of an inch and are so chosen that combinations of lengths in steps of 1 inch may be assembled. The bars are usually supplied in sets, and a typical set of Workshop grade bars consists of the following lengths:

$\frac{1}{2}$, 1, 2, 3, 4, 5, 6, 12, 18 and 30 inches.

ACCESSORIES. The use of slip-gauges and length bars may be extended considerably with suitable accessories. B.S. 888 : 1949 details recommended accessories for slip-gauges (Fig. 14.1), which may be used to build up gap gauges for measuring external diameters (Type "A" and Type "B" jaws), or for measuring internal diameters (Type "A" jaws). Somewhat similar accessories can also be supplied for length bars.

It may be asked if high accuracies in the manufacture and measurement of slip-gauges and length bars are really necessary. It is of interest to consider a cylindrical component having a diametral tolerance of 0·005 in. The maximum allowable size of such a component will be controlled by means of a "Go" ring-gauge and, to leave a reasonable work tolerance for the manufacturer, it is usual to make the tolerance on the ring-gauge about 10 per cent of the work tolerance, i.e. 0·0005 in. Now ring-gauges themselves have to be inspected, and this is frequently done by the use of "Go" and "Not Go" plain plug check gauges. The tolerances in the manufacture of these check gauges will obviously have to be only a small proportion, say 10 per cent, of the ring-gauge tolerance, that is 0·00005 in. In the measurement of the plain plug check gauges slip-gauges will be used, and with these an accuracy of measurement of a *few millionths of an inch* is required to verify that the check gauges are

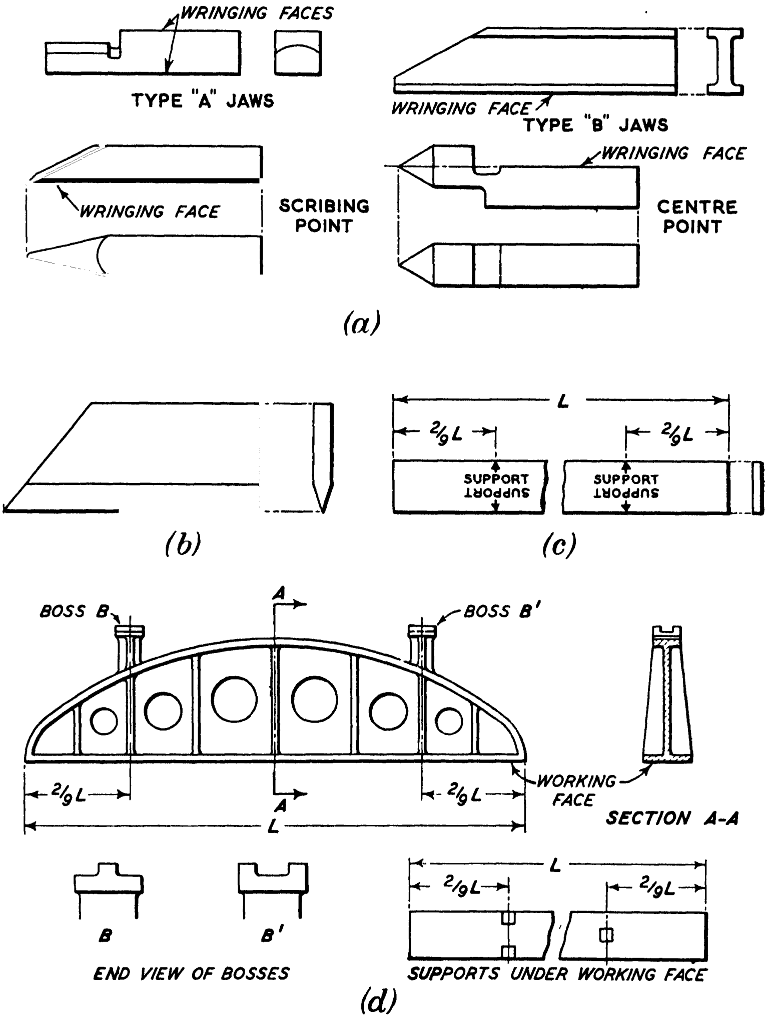


Fig. 14.1. (*a*) Slip-gauge accessories. (*b*) Toolmaker's straightedge. (*c*) Rectangular section straightedge. (*d*) Cast-iron straightedge

between their allowable limits. From this simple example of a component having a tolerance of 0·005 in. it will be seen that it is necessary for the slip-gauges ultimately used as end standards of length to have an accuracy of manufacture and of measurement of only a few millionths of an inch.

EFFECT OF TEMPERATURE ON MEASUREMENT. The lengths of commercial end standards are quoted at a standard temperature of 68° F. (20° C.). It is not necessary that all measurements made by using these standards should be at this standard temperature, providing the standards and the work to be measured have the same coefficient of linear expansion and are at the same temperature. It is of the utmost importance to maintain the standards and work at the *same* temperature if the greatest accuracy of measurement is required. If components are removed from a machine they should be allowed to cool down to the room temperature before any measurements are made, the room temperature should be stable, and there should be no draughts as these cause undesirable temperature gradients.

Commercial Standards of Angle. In the same way as end standards of length may be built up by wringing together slip-gauges, angles may be built up by wringing together angle blocks. These blocks were devised by the late Dr. G. A. Tomlinson, of the National Physical Laboratory, and a set comprises twelve blocks of carefully selected sizes (Fig. 14.2) together with a square block. The upper and lower faces of each angle block are lapped accurately flat and at a certain specified angle to each other. Two angle gauges may be wrung together by either of two ways, to produce an angle between the two unwrung faces which is either the sum or difference of the angles of the two gauges (Fig. 14.2). This property is made use of in building up a series of gauges to produce the required angle. With the set of gauges shown in Fig. 14.2 it is possible to build up any angle from 3 seconds of arc upwards in steps of 3 seconds of arc. For example, if an angle of 33° 5′ 21″ is required this can be built up in the following manner:

$$27^\circ + 9^\circ - 3^\circ + 9' - 1' - 3' + 27'' + 3'' - 9'' = 33^\circ.5'\ 21''$$

Measuring Equipment. When making measurements it is often convenient to place the work on some accurately flat datum surface, such as a *surface plate*, which is generally an iron casting having an accurately flat horizontal upper surface. There are many types and designs of surface plate but they are all as rigid as possible. This rigidity is usually obtained by suitable ribbing on the under surface. The method of finishing the upper surface depends on the accuracy of flatness required; the highest grade plates have a lapped, scraped, or ground finish, but where such precision is not required a planed surface is adequate. A *toolmaker's flat* is a circular hardened steel surface plate having a high-quality lapped finish.

A *Straightedge* provides a standard of straightness by comparison with which the straightness and flatness of a surface can be inspected.

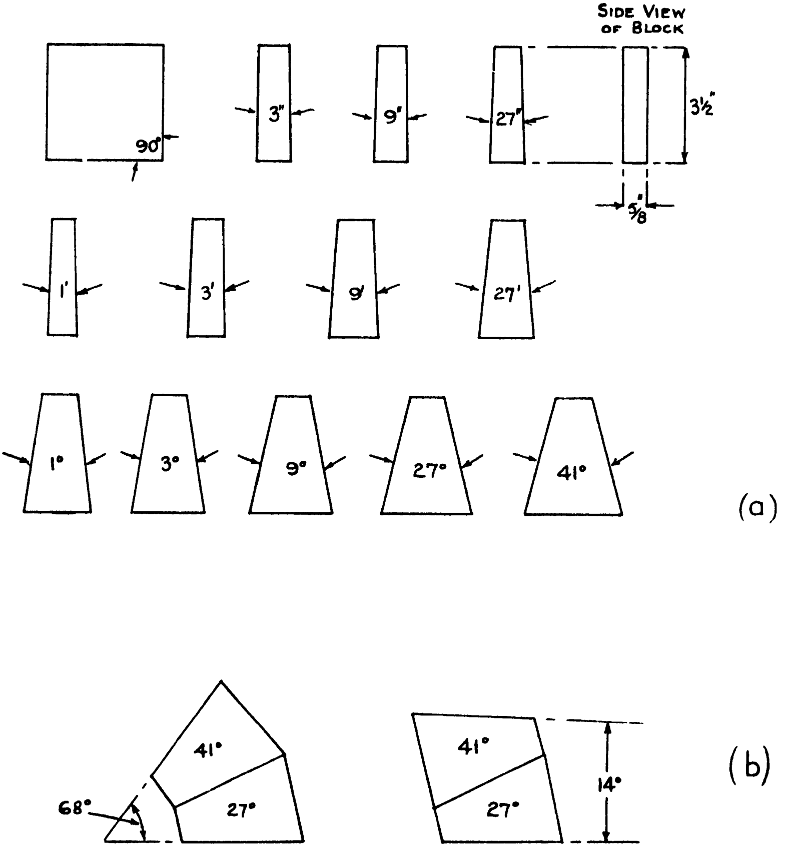


Fig. 14.2. (*a*) Diagram of set of angle gauges. (*b*) Two methods of combining angle gauges

There are three main types (Fig. 14.1), *toolmaker's*, *rectangular section steel*, and *cast-iron* straightedges.

Toolmaker's Straightedges are used for the most accurate work; they are generally short in length and have a hardened bevelled and radiused edge, known as a "knife edge" (Fig. 14.1*b*). For less accurate and larger work the other two types are used.

Large Steel Straightedges are usually of rectangular section, with their upper and lower surfaces accurately flat and parallel. A difficulty arises in the use of long rectangular section straightedges in that if they are placed directly on the work they tend to follow the shape of the work surface, due to their weight and lack of rigidity. For this reason such straightedges of more than 3 feet in length should be supported at a distance from each end equal to two-ninths of their length (Fig. 14.1*c*) so that the flexure is at a minimum. Variations of flatness of the work may then be investigated by measuring the gap between the straightedge and the work with slip-gauges, or by indicating with a dial gauge along the upper surface of the straightedge.

Cast-iron Straightedges are of the bow shape shown in Fig. 14.1*d*. They may be used in the position shown, but with supports under the working face opposite the bosses in order that any flexure caused by the weight of the straightedge is reduced to a minimum. Alternatively they may be used resting on one side, or resting on the two bosses with the working face uppermost. Because of the relatively wide working face it is recommended, in order to avoid any torsional effect, that the straightedges should have a *three-point support* when resting in a vertical position. This is effectively secured when the working face is uppermost by machining the bosses, and when the straightedge is supported on its working face in a vertical position the supports can be placed as in the figure.

Try-squares are used for testing squareness. They consist of a blade of steel fixed rigidly at right angles to a bar, or "stock," of rectangular section. Reference grade squares, which are made to the highest degree of accuracy, have bevelled edges to the blade, but Inspection and Workshop grade squares have blades of rectangular section.

Vernier Callipers (Fig. 14.3) are used for making external and internal measurements. They usually consist of a graduated bar of rectangular section having a measuring jaw made integral with it, and a second measuring jaw which can slide along the bar. A fine-adjustment clamp is attached to the sliding jaw, and, in use, the latter is set to approximately the correct position, the fine-adjustment clamp is then locked in position, and any necessary adjustment to the sliding jaw is made by means of the nut on the screw between the two. The distance between the jaws is given by the reading of the

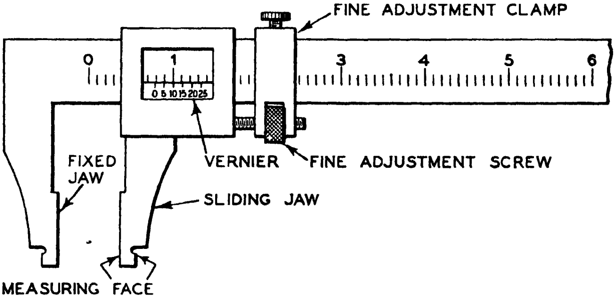


Fig. 14.3. Vernier calliper

sliding jaw on the graduated bar, an accuracy of reading of 0·001 in. being obtained by the use of a vernier. For internal measurements the outer measuring surfaces of the jaws are radiused, and it is usually necessary to add the combined thicknesses of the toes to the scale reading to obtain the required internal measurement.

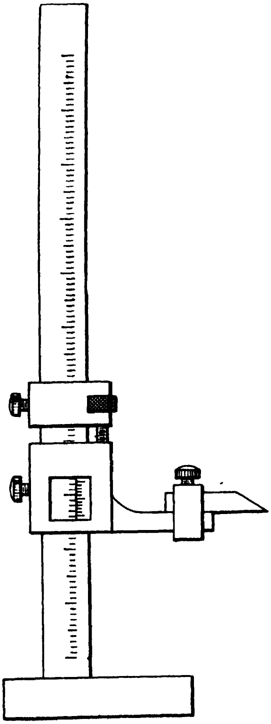


Fig. 14.4. Vernier height gauge

The Vernier Height Gauge (Fig. 14.4) is generally of similar construction, and may be used to measure the heights above a surface plate of various features of work placed on the plate.

The Dial Gauge consists of a spring-loaded measuring spindle which operates a needle pointer, rotating above a circular scale, through a rack and a train of gears. The train of gears is so designed that a small movement of the measuring spindle produces a relatively large movement of the needle pointer. Dial gauges are used to set up work concentrically on a lathe, and to measure differences in dimension; the accuracy with which they can do so depends on the scale magnification of the spindle movement and the accuracy of manufacture of the gears. Differences between readings taken on, say, a height standard and a component should accordingly be kept to a minimum value for the most accurate measurement, as the use of the same part of the dial gauge scale and the same relative position of the gears for both readings reduces errors in measurement to a minimum. They are usually graduated to read $\frac{1}{1000}$ in. or $\frac{1}{10{,}000}$ in. per division.

Vernier Protractors are used to measure angles. They consist of a fixed blade attached to a circular scale, and an adjustable blade which carries an index mark and a vernier. The angle between the two blades can be read to an accuracy of five minutes of arc.

Where a greater degree of accuracy of angular measurement is required a *sine bar* may be used. This consists of a hardened steel bar (Fig. 14.5) having a flat upper surface, and two equal circular pins or rollers inserted in it at the ends of the bar.

The distance l between the centres of the pins is usually made five or ten inches in order to simplify calculations. By inserting slip-gauges h under one of the pins the upper surface of the bar may be set to any desired angle θ, given by the formula $h = l \sin \theta$.

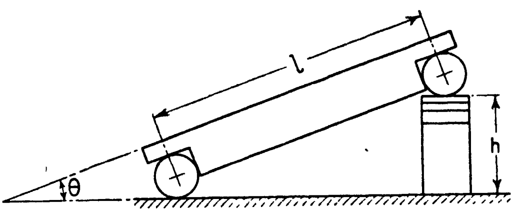


Fig. 14.5. Sine bar

Optical Dividing Heads (Fig. 14.6) are instruments for accurately measuring angles of rotation as when checking the accuracy of a splined shaft. In the example shown the work is suitably connected to the face-plate on the right or between the spindle and a co-axial dead-centre. The rotation of the face-plate imparted by the hand-wheel through a high-ratio gear box can be measured to an accuracy of about six seconds by means of the enlarged image of the scale projected on to the screen above.

Micrometers. When using *hand micrometers* for external dimensions operators may obtain readings which vary slightly, due to the use of different measuring forces. A friction or ratchet drive which slips at a certain torque is often fitted to the end of the thimble, and this enables measurements to be made at a constant force irrespective of the operator. Fig. 14.7 shows a type of micrometer used for internal dimensions.

If an increased accuracy of measurement of external diameters is desired, a *bench micrometer* (Fig. 14.8) may be used. This consists of a base casting to which is attached a micrometer head and a measuring force or *fiducial indicator*. The micrometer head has an enlarged thimble or drum which is graduated directly in 0·0001 in. divisions, and may be read to within a few hundred-thousandths of an inch. The fiducial indicator comprises a spring-loaded sliding plunger operating, through a system of levers, a pointer which moves above a scale engraved with a fixed index mark. Measurements are always made at a constant force, i.e. when the pointer is in line with the index mark. The bench micrometer can be made to cover a range of diameters by adjusting the axial position of the indicator with respect to the micrometer head, and it is therefore necessary to "standardize" the instrument, by observing the reading on a standard

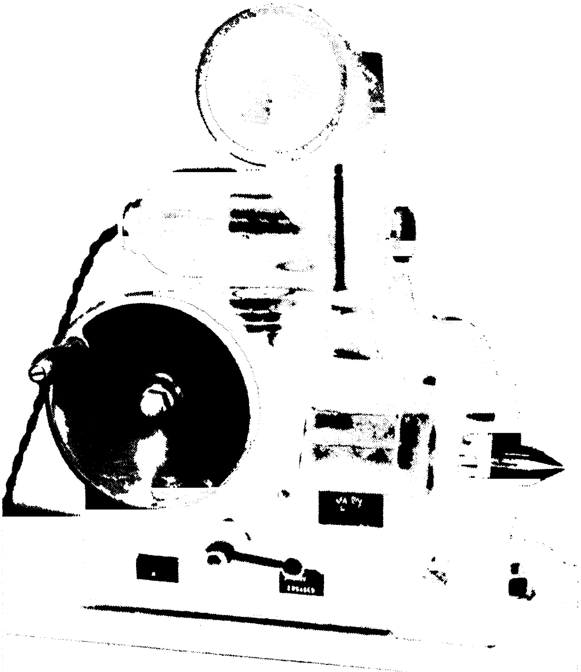


Fig. 14.6. Optical dividing head
(*Coventry Gauge & Tool Co. Ltd.*)

of known size, before any measurements are taken on the work. Addition or subtraction of the difference between the readings on work and standard to the actual size of the latter gives the size of the work.

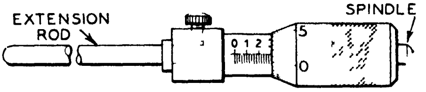


Fig. 14.7. Internal micrometer

Micrometers have to be very accurately made if they are to be regarded as reliable measuring instruments. The accuracy of the pitch of the spindle thread and the flatness and parallelism of the measuring faces are of particular importance; tolerances for these are given in B.S. 870 : 1950. *Micrometers* (*External*).

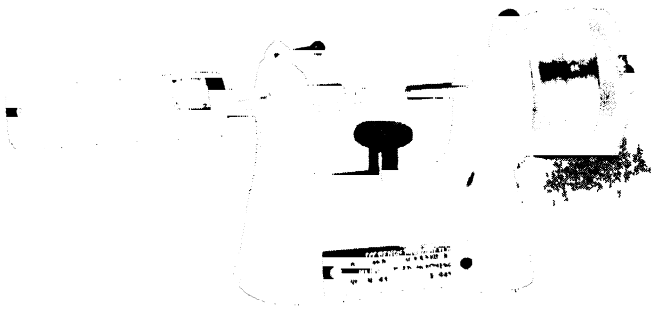


Fig. 14.8. Bench micrometer (based on N.P.L. design)
(*Sigma Instrument Co. Ltd.*)

Comparators determine the size of a component by comparing its size with that of a known standard. They have a measuring head with a spindle whose amplified movements are indicated on a scale. The method of amplification may be by mechanical, electrical-optical, or other means; with the necessarily restricted size of the scale the higher the degree of amplification the smaller is the range of size which can be accommodated at one setting of the measuring head, and the nearer must the size of the standard approach the size of the component.

Vertical Comparators have the measuring head mounted above a work table on a robust stand, and components of widely varying sizes can be accommodated by moving the measuring head up or down the vertical column. The spindle in the measuring head of the comparator shown (Fig. 14.9) has a measuring range of 0·006 in., and a mechanical amplification of 1000 : 1, so that a spindle movement of 0·001 in. produces an indicating pointer movement of one inch on the scale. The instrument is first set by means of a combination of slip-gauges, or other standards, resting on the small work table. The workpiece is then substituted for the standard and the difference in height measured.

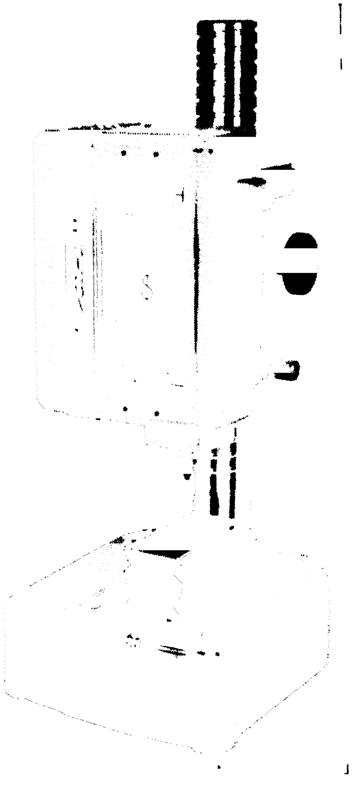


Fig. 14.9. Vertical comparator
(*Sigma Instrument Co. Ltd.*)

Horizontal Comparators comprise essentially a measuring head and a fixed anvil mounted respectively on two brackets which can be moved along a rigid horizontal bed to accommodate different sizes of components. The latter are mounted on a work table that has a movement horizontally and vertically, and can also be rotated and tilted. External and internal dimensions may be measured with special contact jaws. The instrument is standardized for internal measurements by setting the fixed anvil and measuring spindle at a known distance apart with a built-up gap of slip-gauges, and observing the reading of the indicating head. Horizontal comparators are particularly suitable for the internal measurement of plain and screw rings.

A Diameter-measuring Machine will conveniently and accurately measure external diameters (Fig. 14.10). It consists of a rigid base casting carrying centres on which the work is mounted, a lower carriage which can move freely on the base casting in a direction parallel to the axis of the centres, and an upper carriage mounted on the lower carriage so that it can move freely in a direction perpendicular to the axis of the centres. The upper carriage carries a micrometer head with a large-diameter drum opposed to a fiducial indicator similar to that of the bench micrometer. The measuring axis of the micrometer and the fiducial indicator are perpendicular to the axis of the centres; this type of instrument is particularly suitable for measuring the *major*, *effective* and *minor diameters* of external screw threads.

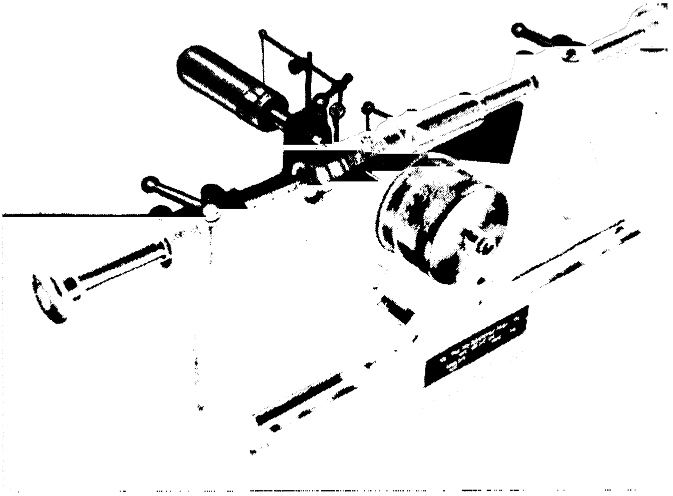


Fig. 14.10. Diameter-measuring machine (based on N.P.L. design)
(*Sigma Instrument Co. Ltd.*)

A *Screw-thread Micrometer* may be used to measure the effective diameters of external screw threads if less accuracy is required than that given by a diameter-measuring machine.

Pitch-measuring Machines will measure the pitches of external and internal screw threads. A base casting carries centres on which are mounted the screw plug to be measured. A carriage sliding on the base casting in a direction parallel to the line of centres and operated by means of a micrometer screw, carries an indicating stylus, which, when inserted in a thread groove, contacts the flanks at the effective diameter. The stylus is engaged with the screw thread and moves up the flank of one thread and down into the next as the micrometer is rotated. When the stylus reaches its lowest position in successive thread grooves and contacts both flanks simultaneously, as shown by the indicator pointer coming opposite a fixed index mark, the micrometer readings are observed, and these give a measure of the pitch. The pitch of screw rings may be measured by mounting them on a face-plate that can be attached to one of the centres, and by using a special attachment to the indicator.

Optical Projection is particularly suitable for the examination of profiles and thread forms. An approximately parallel beam of light from the condensing lens of the lamp-house strikes the profile to be projected and then passes through the projection lens to produce a magnified image of the component profile on a suitable screen, where it may be compared with an enlarged diagram of the correct profile. Common magnifications obtained on such instruments are 25, 50 or 100 times the actual size of the profile, and, with a good projection lens, it is possible to measure the component profile to an accuracy of ± 0·0003 in. at a magnification of 50.

Horizontal projectors have the disadvantage of being large, and the *vertical projector* operating on the same principle is much more compact although, in general, the screen is much smaller.

Toolmakers' Microscopes are similar to vertical optical projectors in that a magnified image of the component is produced which may be thrown upon a screen or viewed through a microscope eyepiece. The component, however, is mounted on a horizontal table which has transverse and longitudinal movements, normal to the optical axis, controlled by micrometer heads; these usually have a range of only one inch, but larger movements of the work table can be accurately measured by inserting slip-gauges between the micrometer spindles and abutments on the work table. By moving the work table through a known distance in a plane perpendicular to the optical axis of the instrument the disadvantage of the small field of the lens is overcome.

Air Gauges. A highly specialized type of measuring machine which has found widespread application in industry is the air gauge. The principle on which this operates is based on the measurement of the change of pressure or velocity of flow behind an orifice due to the escape of air through the latter. The effective size of the orifice is controlled by the diameter of the workpiece which is required to be measured. As the diameter varies, so the effective size of the orifice varies, resulting in a corresponding variation in the pressure or velocity of flow behind the orifice. A measure of the size of the workpiece is obtained by this change of pressure or velocity, as indicated by a manometer or other suitable means of measurement.

The practical applications of air gauging in Great Britain are due mainly to the Solex Company, which has been responsible for much of the development work in connection with air gauging.

Possibly the most popular application has been to the measurement of the bores of cylinders, and Fig. 14.11 shows a plug gauge designed for this purpose. The difference in levels "h" indicated by the manometer is a measure of the size of the cylinder. As air gauges are comparators they have to be set by means of a suitable setting standard, which in this case would be a ring gauge.

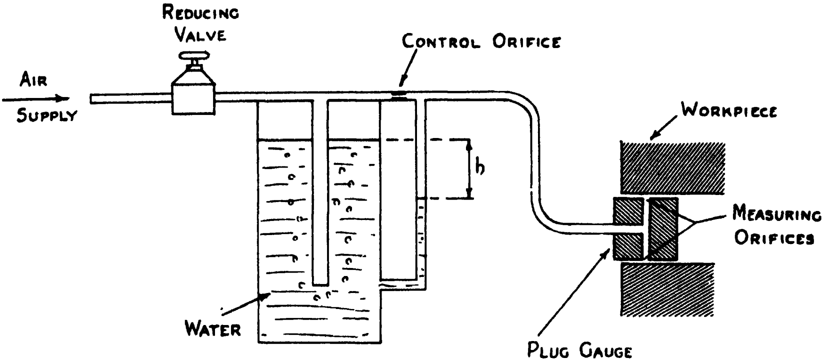


Fig. 14.11. Low-pressure air gauge for measuring bores of cylinders

A recent development is high-pressure air gauging, in which air from the ordinary compressed air system in engineering works may be used. The basic principles are very similar to the low-pressure system. The air in a reservoir is maintained at a constant pressure of say 30 lb. per square inch by a special reducing valve, and then passes through the control orifice of a fine regulating valve to the measuring orifice. The pressure in the pipe line between the control and measuring orifices, and the pressure in the reservoir may be measured by using Bourdon pressure gauges.

For Bibliography see end of book.

CHAPTER XV

INSPECTION: I

LIMITS AND FITS. CONTROL BY MEASUREMENT

By L. W. NICKOLS

Inspection is the process of examination as a result of which a component is accepted and passed on to the next process, or rejected and probably scrapped. If the percentage of rejects becomes too high the production processes must be investigated to find the cause. In the production of large quantities, all similar components must be interchangeable, must assemble with their mating components, and must function satisfactorily without the need for hand fitting or adjustment. It is impracticable to work to an extreme degree of accuracy; some variations in size must be allowed, according to the particular article or the type of work it has to do. The whole success of mass production depends on the satisfactory control of the component sizes, so that they fall within their allowable ranges. This involves an efficient scheme of dimensional inspection between production and assembly line. Dimensional inspection may be carried out by means of a limit gauging system or by direct measurement; this includes "quality control".

Limits, Fits, Tolerances, and Allowances. Consider a shaft running in a plain bearing. The basic diameter for shaft and bearing is calculated from the load to be transmitted by the shaft and the materials to be used. For correct functioning and ease of assembly there must be a minimum clearance (allowance) between the shaft and the bearing; too large an allowance will result in unsatisfactory service while too small will increase assembly difficulties, cause overheating in use, etc.

It is impossible to make the shafts and bearings to their exact theoretical design sizes by economic production methods, and thus certain tolerances are permitted which should be as large as the functioning conditions permit.

A logical method of deriving the tolerances on the diameters of the shaft and bearing under consideration is as follows: in Fig. 15.1*a* the minimum permissible clearance between the assembled shaft and bearing (when new) is first chosen so that the assembly functions satisfactorily from the start and allows a reasonable amount of wear to occur before it becomes unfit for service. The difference between the *minimum* permissible clearance and the *maximum* permissible clearance gives the *sum* of the permissible tolerances on the shaft and the bearing.

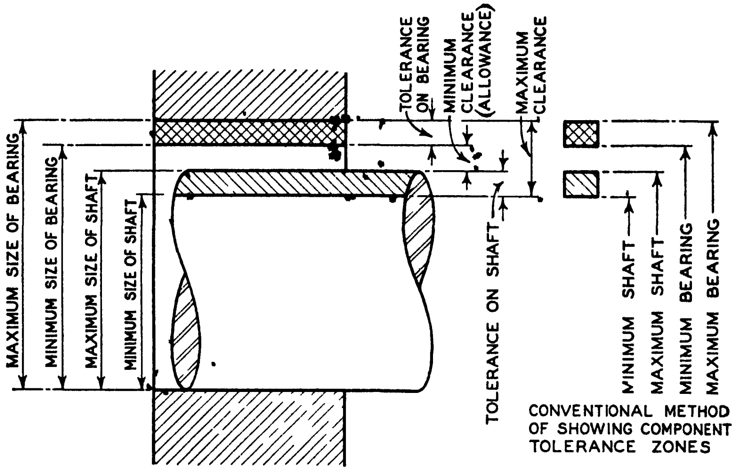


Fig. 15.1*a*. Tolerance zones for shaft bearing

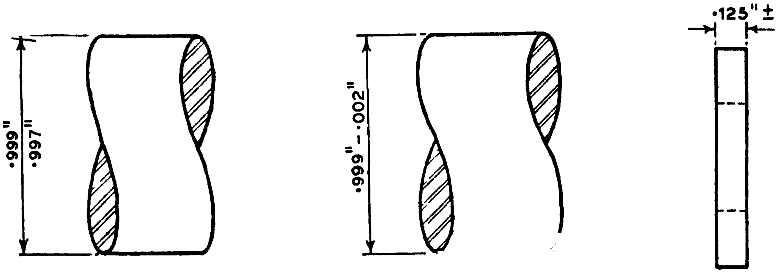


Fig. 15.1*b*. Methods of stating limits and tolerances

The proportions of this sum which may be allocated to shaft and bearing respectively should depend on the accuracy of the methods of manufacture for the shaft and for the bearing. In general, holes are more difficult than shafts to manufacture, as far as tolerances are concerned, and it is reasonable to allocate a larger proportion of the tolerance sum to the tolerance on the bearing.

From this it will be seen that if the functioning and assembly of the mating shaft and bearing are to remain unaffected by the application of the tolerances to the design sizes of the shaft and bearing, then the actual sizes may only be allowed to vary from the design sizes in one direction, namely, not to decrease the minimum clearance. This is *unilateral* tolerancing and is recommended for mating parts; a unilateral tolerance is disposed wholly on *one* side of the design size.

An alternative method is *bilateral* tolerancing where the size of the component is allowed to vary in *both* directions from its theoretical design size. This system is suitable for non-mating components where any clearance between a component and the mechanism to which it is fitted plays no part in the functioning of the mechanism, e.g. between the outside diameter of the flywheel on an automobile engine and the inside diameter of the flywheel housing. Bilateral tolerances are disposed equally on both sides of the design size.

By the application of a tolerance to a design size the two sizes may be calculated between which the actual size of a component may be permitted to vary, and these two sizes are termed *limits of size.*

There are various methods of stating limits and tolerances on the drawing of a component (Fig. 15.1*b*). That recommended is to state the maximum and minimum limits of size, the tolerance then being the difference between them. A second method gives the design size and its tolerance; this is illustrated in the diagram both for the Unilateral tolerance and Bilateral tolerance.

In the example of a shaft running in a bearing the minimum clearance was termed an "allowance." While this is correct for this particular example the term "allowance" has a wider application and may be defined as follows: an *allowance* is the difference between the low limit of size of a hole (or female feature) and the high limit of size of the mating shaft (or male feature).

If the smallest allowable hole is larger than the largest allowable shaft then there will always be a clearance between the two and we have a *clearance fit.*

If, on the other hand, the smallest allowable hole is smaller than the largest allowable shaft we have two possible classes of fit. Fig. 15.2*a* shows one possibility, in which the allowance is greater than the sum of the tolerances on the mating parts; there will never be any clearance between the mating parts which can only be assembled by the *use* of force. This is an *interference* fit. The other possibility is when the allowance is less than the sum of the tolerances on the mating parts (Fig. 15.2*b*) and we have a clearance fit or an interference fit depending on the actual sizes of the mating parts between their allowable limits; this is a *transition* fit.

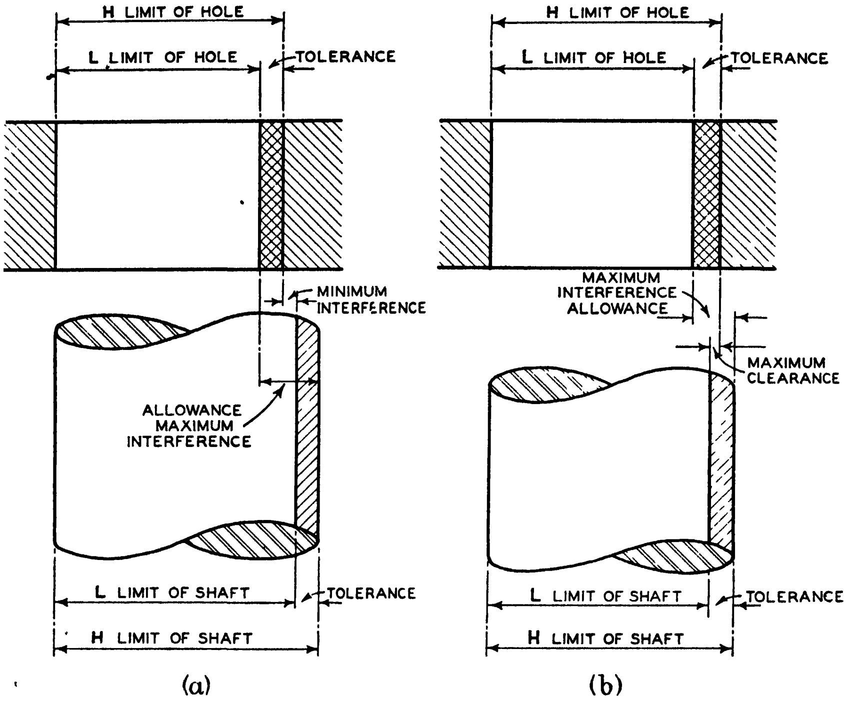


Fig. 15.2. (*a*) Interference fit. (*b*) Transition fit

It will be seen that the different functional requirements can be satisfied by adjusting the allowance. For example in a clearance fit, if a *slide* fit is required, the allowance will be small. A *normal running* fit may be produced by increasing the allowance, and a *slack running* fit by a further increase.

An increase or decrease in the allowance may be brought about by any of three ways:

1. By keeping the hole constant and obtaining the desired degree of fit by altering the size of the shaft. Such a system of fits is said to be on a *hole basis*, and is strongly recommended as it permits the use of standard sizes of drills, reamers, etc., and so reduces tool costs.

2. By keeping the shaft constant and obtaining the desired

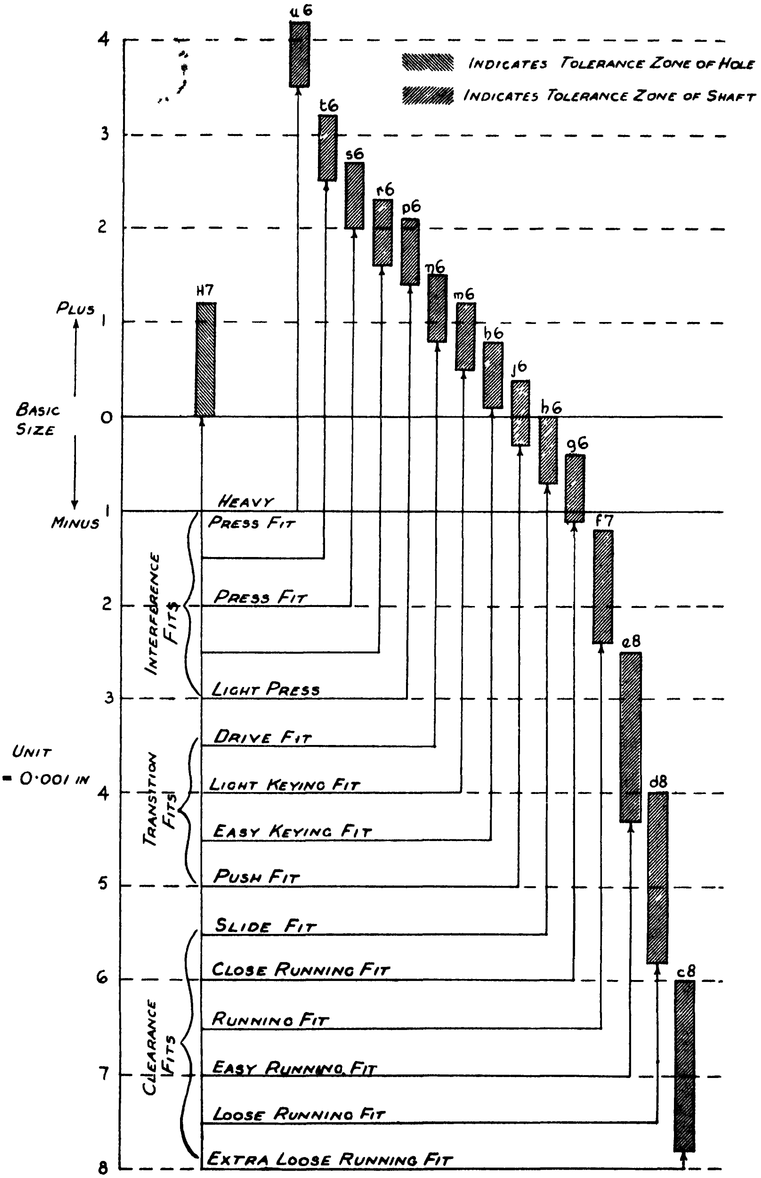


Fig. 15.3. Relative dispositions and magnitudes of the tolerance zones of various grades of a 2 in. diameter shaft which may be associated with a 2 in. H7 hole. (From B.S. 1916, 1953)

degree of fit by altering the size of the hole. The resulting system of fits is said to be on a *shaft basis* and has the advantage that standard diameter bar stock may be used.

3. By adjusting the sizes of hole *and* shaft. This method is *not* recommended as its disadvantages are obvious.

A Limits and Fits System lays down a complete series of limits and tolerances covering a wide range of diameters of shafts and holes, and the required degree of fit for any one nominal diameter may be obtained by selecting suitable limits from the system. As a guide to designers, the British Standards Institution has issued a Standard B.S. 1916 : 1953, *Limits and Fits for Engineering*, based on the ISA* system which has been in general use on the Continent for many years. This system provides 21 types of fit, ranging from very loose clearance fits to extreme interference fits. The use of a unilateral hole basis system is recommended, but limits and tolerances are also given for a full range of holes which may be used in a shaft basis system if this is so desired. For each diameter range there are 16 grades of tolerance, designated IT 1 to IT 16 respectively, each grade of tolerance being, in general, a multiple of a fundamental tolerance unit i where

$$i\,(0{\cdot}001\text{ in.}) = 0{\cdot}052\,\sqrt[3]{D} + 0{\cdot}001\,D$$

and D (in.) is the geometric mean diameter of the range.

The *positions* of the limit of each tolerance zone nearest the basic size are indicated by 21 letters, capital letters being used for holes and small letters for shafts. Thus H7 indicates a hole having a position H in relation to the basic size and a tolerance grade IT 7.

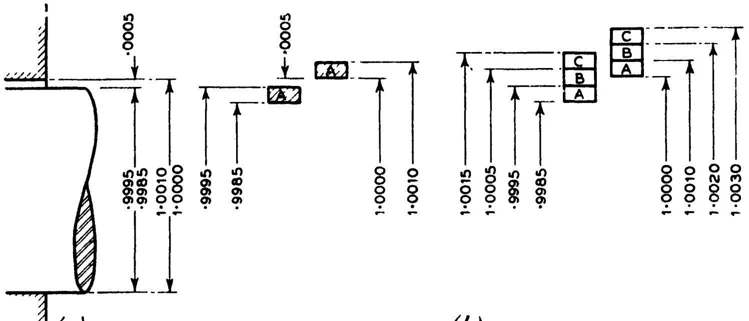
The complete fit, comprising a hole and its associated shaft, would be indicated, for example, as 1·25 H7·g6, where 1·25 is the basic size, but on production drawings it is usual to put down the actual limits of size of the hole and shaft.

The number of possible combinations of holes and shafts in the ISA system may seem excessive, but it is intended that each industry or firm should use only those fits which it has found from experience to be necessary in manufacturing its products. In practice the unilateral hole basis system, based on the H hole is most generally used.

The relationship between the various grades of holes and shafts may be more easily understood by reference to Fig. 15.3, which shows the relative dispositions and magnitudes of the tolerance zones of various shafts which may be associated with a H hole.

* International Federation of National Standardizing Associations.

Selective Assembly. In certain component designs the maximum permissible tolerance determined by the functioning requirements may be considerably smaller than can be achieved by the manufacturing process it is desired to use. For example, consider two mating component diameters having an allowance of 0·0005 in. and tolerance of 0·001 in. (Fig. 15.4*a*). The maximum possible clearance, when both components are at their minimum metal limits (smallest shaft and largest hole) is 0·0025 in. and this is the maximum permissible clearance which will provide a reasonable amount of wear with correct functioning; it cannot therefore be increased.



(*a*) THEORETICAL TOLERANCES AND ALLOWANCE REQUIRED FOR CORRECT FUNCTIONING

(*b*) PRACTICAL LIMITS OF SIZE WHICH PERMIT THEORETICAL FUNCTIONING REQUIREMENTS TO BE SATISFIED

Fig. 15.4. Diagram showing application of selective assembly

If we assume that it is desired to manufacture the components by a process which cannot produce them economically to a tolerance of less than 0·003 in. we should use the method of *selective assembly.* This process can be illustrated by using the case just outlined. Let the tolerances on the external and internal diameters be increased in the same direction to 0·003 in. After manufacture, the components are sorted into three grades,. A, B, and C, each grade of external diameter having the same relation to its correspondingly lettered grade of internal diameter as in Fig. 15.4*b*, namely: 0·0025 in. maximum clearance and 0·0005 in. allowance. Assembly of external diameters with internal diameters of the same grade will then satisfy the theoretical functioning requirements.

The method of selective assembly has considerable advantages in enabling otherwise unsuitable manufacturing methods to be used, but it should be remembered that interchangeability of mating components is limited because only correspondingly lettered grades must be assembled together, and this may lead to the stocking of an increased number of spare components by the manufacturer with the additional problems of marking and storage.

Control of Size by Measurement. If component tolerances are very small the provision of a suitable limit gauging system presents considerable difficulties because of the correspondingly small tolerances required for the gauges. Gauges made to these small tolerances have a correspondingly short life in service before they wear to the allowable limit; moreover, they are expensive to make. For these reasons the British Standard for Plain Limit Gauges, B.S.969 : 1953, recommends that external diameters having tolerances less than 0·0007 in. should be measured, rather than be gauged with ring or gap gauges. The control of the component size by direct measurement has the advantage of obtaining the sizes of the components to form a useful guide to the tool-setter and the inspector. *Measuring machines*, in general, are not so robust as limit gauges and require more skill to work; also they are usually more complicated, specialized, and expensive, as they operate on mechanical, electrical, optical, or pneumatic principles.

Quality Control is the name given to a method of inspection whereby the quality of the whole volume of production is assessed by applying the mathematical theory of probability to the measurements obtained on samples of average production taken in a systematic manner. This method is particularly suitable for large quantity production where full inspection of all the components is too costly, and for providing a clear indication of the rate at which deterioration of the cutting tool or of the machine components is affecting the product, enabling appropriate action to be taken actually *before* articles of an unsatisfactory quality are produced.

If a large batch of components is taken off a machine and measured, a graph may be plotted (Fig. 15.5) showing the number of components of any one size. If the conditions under which the machine is working are constant throughout the production of the batch, i.e. no adjustment is made to the machine or the manufacturing material, then the distribution curve is known as a "Gaussian" or "Normal" distribution curve. It may be defined mathematically by two quantities: (*a*) the arithmetical average value $\overline{X}$ of all the measurements of the batch of components, and (*b*) a quantity σ known as the "standard deviation" of the measurements.

The "standard deviation" is the root mean square (i.e. the square root of the average value of the squares) of all the varying differences between individual measurements and the average value.

In Fig. 15.5 it may be seen that very few measurements fall between the sizes indicated by *e* and *f*, and *g* and *h* respectively. It may be calculated mathematically, for example, that for a true "Gaussian" distribution curve the ranges of size between $\bar{X}$ and f and g respectively will be equal to $3{\cdot}09\sigma$, if it is assumed that 1 in 1000 measurements falls between *e* and *f*, and between *g* and *h*. Hence we may say that only one component in five hundred will fall outside the *control limits f* and *g*.

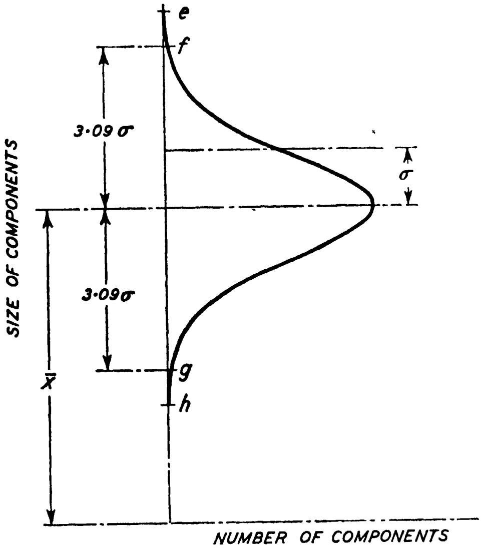


Fig. 15.5. "Gaussian" or "Normal" distribution curve

It is possible by taking measurements on a large number of components from a machine in perfect working order to calculate $\bar{X}$ and σ, and hence derive for the machine the mathematically suitable control limits outside which only a certain percentage of the measurements will fall. This is the main principle underlying quality control, as the control limits define a standard of performance for a machine in good working order. It should be emphasized that the tolerance defined by control limits may not bear any relation to the tolerance specified on the drawing of the component. In most cases functioning considerations play a larger part in determining the drawing tolerance than the method of manufacture, and the individual type of machine tool used in the component manufacture is not considered, as long as the functioning or drawing tolerance is also practicable for manufacture. The control limits must fall, therefore, inside the tolerance zone of the component.

Quality control is applied to the manufacture of components in the following way. In the first place measurements are not taken on all components but on certain numbers at regular intervals. The control limits on such *samples* are necessarily different from the control limits on *all* the components, and the *mathematical theory of probability* has to be applied to the measurements of samples to ascertain the probable standard of quality of all the components. There are four B.S. *Specifications dealing with Quality Control*, B.S. 600 : 1935, B.S. 600 R : 1942, B.S. 1008 : 1942 and B.S. 2564 : 1955, and they show how control limits are calculated for various sample sizes. Having decided on a suitable number of components in each sample, measurements are made on a large number of successive samples obtained from the machine while in proper working order. From the measurements on each sample may be derived two quantities: (*a*) The arithmetical average size of the sample, which indicates any tendency for the machine to depart from its original setting, say, through tool wear, and (*b*) The standard deviation σ which is a measure of the uniformity of the product. If, as is usual, the size of the sample is below 10 components, then the *range* of sizes in the sample, i.e. the maximum size in the sample minus the minimum size, is usually taken as representing the uniformity of the product. The mean average size and the mean range of all the samples are then calculated. With this information, control limits for the average size and range of each sample may be obtained from the B.S. Specifications.

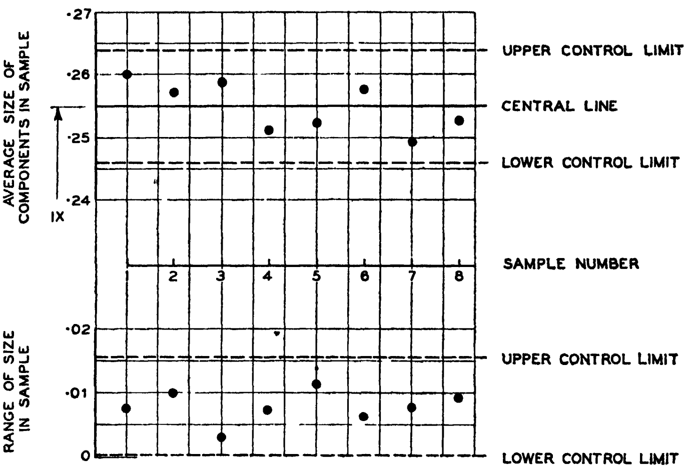


Fig. 15.6. Control charts for average size and range

The control limits so obtained are plotted on two horizontal charts (Fig. 15.6). As already stated, the control limits define a standard of performance for a machine in good working order, and hence values obtained from further samples should always fall between the appropriate control limits if the machine is functioning correctly—as indicated by the points on the two charts. If points plotted for succeeding samples tend to move outside the control limits then trouble should be suspected; it may not be due to any fault or normal wear in the machine but to external changes, such as a change of manufacturing material, etc.

The advantage of quality control when properly applied is that it provides a means of watching the development of factors which if unchecked will have a serious effect on production, and thus of taking remedial action in good time.

For Bibliography see end of book.

CHAPTER XVI

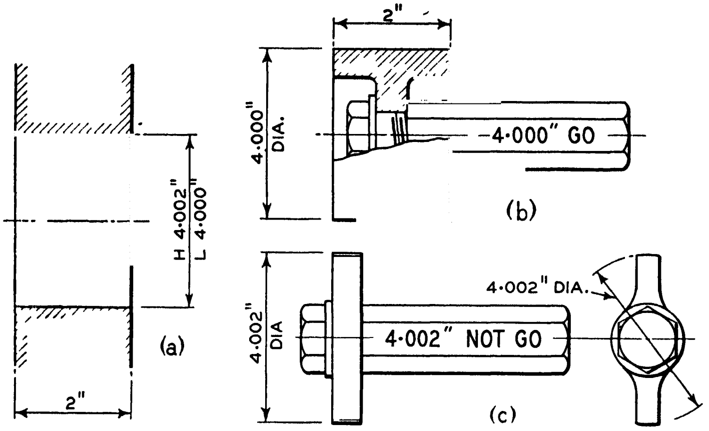
INSPECTION: II

CONTROL BY GAUGING

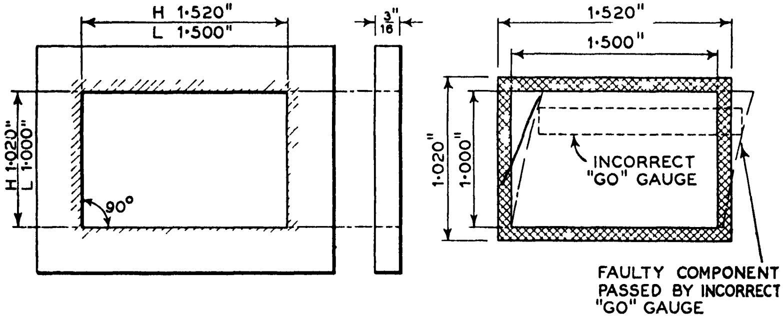
By L. W. NICKOLS

Limit Gauges. Limit gauges are applied to components to verify that the sizes of the latter are between the permitted limits. Consider the bearing in Fig. 16.1*a*, having specified limits of L. 4·000 in. and H. 4·002 in. on its internal diameter. A suitable limit gauging system for this dimension consists of a ***plain plug gauge*** made to the ***minimum***, and a ***bar gauge*** made to the ***maximum*** allowable diameter of the bearing. Two such gauges are shown in Figs. 16.1*b* and *c*. The internal diameter of the bearing is between its allowable limits if the plain plug gauge enters for the full length of the bearing, while the bar gauge refuses to enter it anywhere when applied with its measuring plane normal to the longitudinal axis of the bearing. From its function the plain plug gauge is known as a "Go" gauge, and the bar as a "Not Go" gauge. "Go" and "Not Go" gauges are made respectively to the maximum metal and minimum metal limits. The maximum metal limit is the H. limit of an external diameter and the L. limit of an internal dimension. The minimum metal limit is vice versa.

An important principle of design in limit gauges, known as Taylor's principle, is that the "Go" gauge should incorporate the maximum metal limit of as many dimensions as it is convenient and suitable to gauge in one operation, but separate "Not Go" gauges should be used to check the minimum metal limit of each dimension in turn. The reason for this may be more clearly understood by reference to the lower part of Fig. 16.1. A 1 in. × 1½ in. rectangular hole at (*d*) has a tolerance of 0·020 in. on its sides; and (*e*) shows the shaded tolerance zone in which the sides of the hole must fall in order to comply with the requirements of (*d*). If separate "Go" bar gauges were used to control the L. limits of the sides of the hole it might

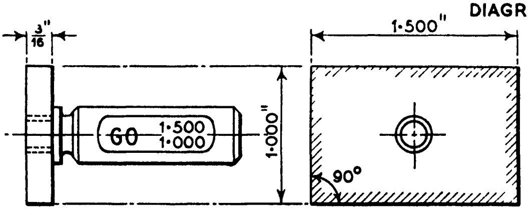


COMPONENT AND SUITABLE LIMIT GAUGING SYSTEM.



(d) COMPONENT

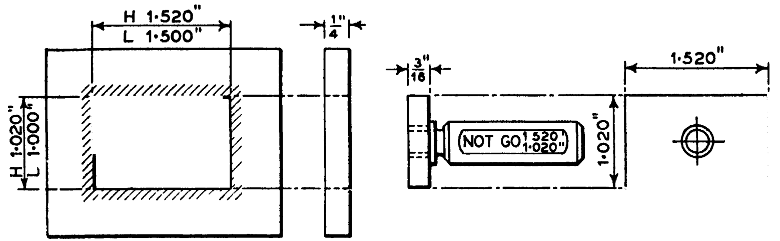
(e) COMPONENT TOLERANCE ZONE DIAGRAMMATIC



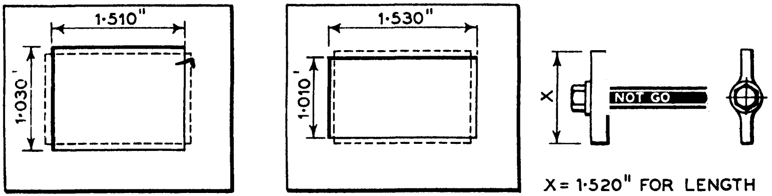
(f) CORRECT FULL FORM "GO" GAUGE

Fig. 16.1. Principle of design of "Go" gauge

have the shape indicated by the chain-dotted line in (*e*), and still be accepted as satisfactory by these "Go" gauges. The only satisfactory "Go" gauge which adequately ensures that the shape of the hole nowhere encroaches on its maximum metal limit is the "Go" gauge shown at (*f*), which incorporates the low limit of both the toleranced dimensions of the component, and is known as a "full form" gauge.



(a) COMPONENT (b) INCORRECT "NOT GO" GAUGE



X = 1·520" FOR LENGTH OF HOLE
X = 1·020 FOR BREADTH OF HOLE

DOTTED LINE INDICATES SHAPE OF "NOT GO" GAUGE

(c) FAULTY COMPONENTS PASSED BY INCORRECT "NOT GO" GAUGE (d) CORRECT "NOT GO" GAUGES

Fig. 16.2. Principle of design of "Not Go" gauge

If a "Not Go" gauge were designed to control simultaneously the minimum metal limit of more than one dimension it might pass, as satisfactory, components which are outside their minimum metal limits. For example, Fig. 16.2*b* shows an incorrect "Not Go" gauge designed to control the minimum metal limit of the component shown in (*a*). This gauge would be a "Not Go" when applied to components well outside the allowable limits (as in *c*). Correctly designed "Not Go" gauges each control the minimum metal limit of one dimension *only* (*d*).

Gauge Tolerances and their Disposition. In theory, gauges should be made exactly the same size as the component limit which they control, but in practice this is not an economical proposition; it is just as essential to allocate a suitable tolerance to a gauge as it is to the component. The principle adopted by the British Standards Institution when laying down limits and tolerances for gauges used on cylindrical work is that no work should be accepted as satisfactory whose size is outside the specified limits of size. This ideal is achieved, as far as is practicable, by placing the tolerance zones of "Go" gauges within the work limits and the tolerance zones of "Not Go" gauges just outside and bordering on the "Not Go" limit of the work (Fig. 16.3*a*). The same gauges are intended to serve for both workshop and inspection purposes. It will be noted from Fig. 16.3*a* that the use of a "Go" gauge may reduce the next component tolerance available to the manufacturer by the amount of the gauge tolerance, and the "Go" gauge tolerances should, therefore, be as small as is reasonably practicable.

It is usual to provide a margin for wear on the "Go" gauge, when the component tolerance is sufficiently large; this is done by moving the "Go" gauge tolerance zone further into the component tolerance zone, and reducing the net component tolerance even more.

For the assistance of gauge designers the British Standards Institution has published two Standards dealing with gauge tolerances, viz.:

B.S. 919 : 1952, *Screw Thread Gauge Tolerances.*

B.S. 969 : 1953, *Tolerances for Plain Limit Gauges.*

B.S. 919 : 1952, gives recommended screw gauge tolerances and their disposition with respect to the component tolerance zone, for a range of diameters. The tolerances are as small as is reasonably practicable.

B.S. 969 : 1953, gives recommended tolerances, and their disposition with respect to the component tolerance zone, for plain limit gauges, such as *plain plug*, *ring*, and *gap gauges*. The gauge tolerances given cover a range of component tolerances, and have values about 10 per cent of the latter.

Adjustable Gauges. Wear on certain types of gauges, such as gap gauges, may be compensated by making them adjustable, and in such cases it is unnecessary to allow a wear margin for the "Go" Workshop gauge. Fig. 16.3*b* shows a type of gap gauge having anvils which may be adjusted by means of set screws A and B with respect to the long anvil C. The gap between the anvils may be set to any predetermined size by inserting a slip-gauge combination of the required size between the two gauging anvils, and then closing in the adjustable anvil until the slip-gauge combination just fits the gap, when the anvil may be locked in position.

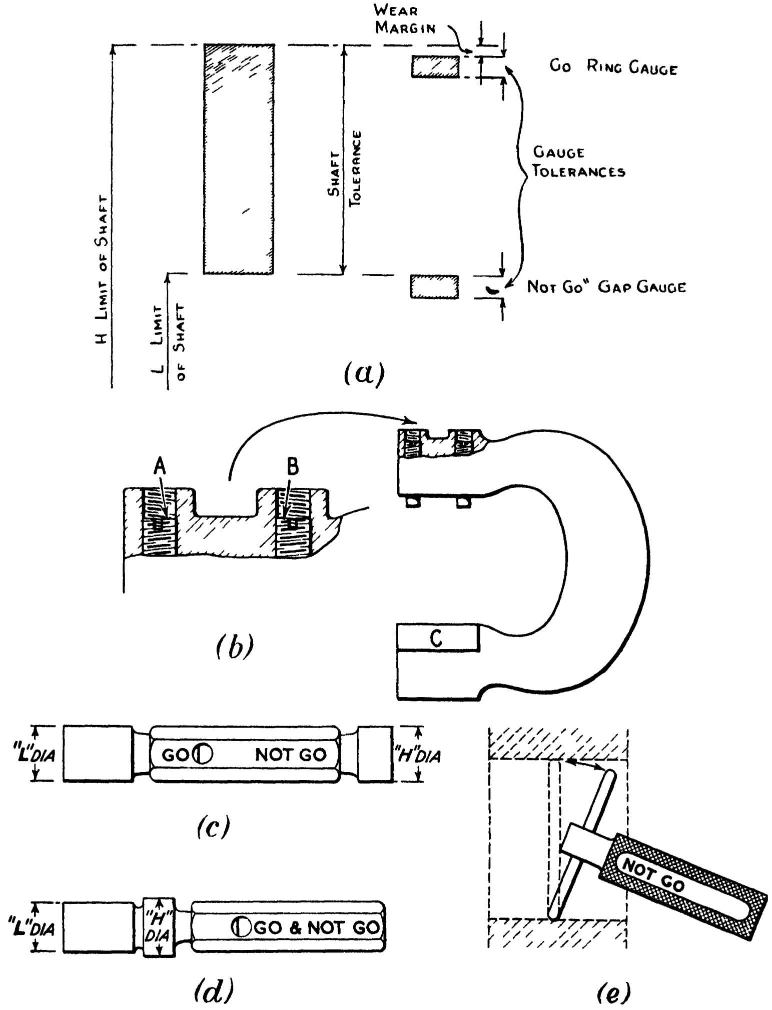


Fig. 16.3. (*a*) Disposition of gauge tolerance zones with respect to component tolerance zone of shaft. (*b*) Adjustable "Go" and "Not Go" gap gauge. (*c*) Double-ended "Go" and "Not Go" plain plug gauge. (*d*) Single-ended "Go" and "Not Go" plain plug gauge. (*e*) "Not Go" pin gauge

Advantages and Disadvantages of Limit Gauging Systems. Limit gauges for controlling the size of components can be used by unskilled labour. Inspection by the use of gauges is rapid; the gauges are usually of a simple robust construction, and, with reasonable care, are not easily damaged. A close watch should, however, be kept on the sizes of limit gauges so that wear beyond that allowable may be detected. A criticism of limit gauging systems is that they give no indication of the actual size of the component within its tolerance zone, and consequently no warning of possible trouble until the gauges start rejecting components, when a considerable number of faulty components may have been made. Also, when the components are outside the allowable limits the gauges give no indication of the magnitudes of the errors in the dimensions gauged.

Types and Uses of Limit Gauges

PLAIN PLUG GAUGES are used for gauging internal diameters and are of the "Go" and "Not Go" variety. Theoretically, "Not Go" plain plug gauges should not be used as they may allow oval components to be passed as satisfactory which have maximum diameters larger than the permitted upper limit. In practice such "Not Go" gauges are commonly used for sizes up to about 2 in. diameter.

Fig. 16.3*c* illustrates a double-ended "Go" and "Not Go" plain plug gauge having detachable gauging plugs which may be replaced when worn. It should be noted that the "Go" plug gauge usually has a length at least equal to that of the component. The "Not Go" plug gauge is made appreciably shorter.

Fig. 16.3*d* shows an alternative design of plug gauge in which the "Not Go" plug is at the rear end of the "Go" plug. Whilst this design of gauge is quicker to use it has the disadvantage that the life of both plugs is governed by that of the "Go" plug unless the practice is adopted of reconditioning the worn "Go" plug by chromium plating and regrinding to size.

PIN AND BAR GAUGES are generally "Not Go" gauges for internal diameters. An example of a bar gauge has already been shown in Fig. 16.1*c*. Pin gauges may be used to verify that the H. limit of a hole has not been exceeded at any part of the bore. For this purpose the gauge is inserted in the hole at an angle (Fig. 16.3*e*) and is then rocked in an axial plane about one end. If the hole is oversize it will be possible to rock the gauge so that it passes through the normal position.

PLAIN RING GAUGES are generally used as "Go" gauges for external diameters and are of simple design (Fig. 16.4*a*).

GAP GAUGES serve as "Not Go" gauges for external diameters, but are sometimes combined with "Go" gauges as in Fig. 16.4*b*.

When using gap gauges care should be taken to gauge the component in a number of positions along and around its surface, otherwise possible ovality outside the limits of size may be overlooked. Gap gauges have the advantage over ring gauges in that they may be applied to components when the latter are mounted between centres on the machine.

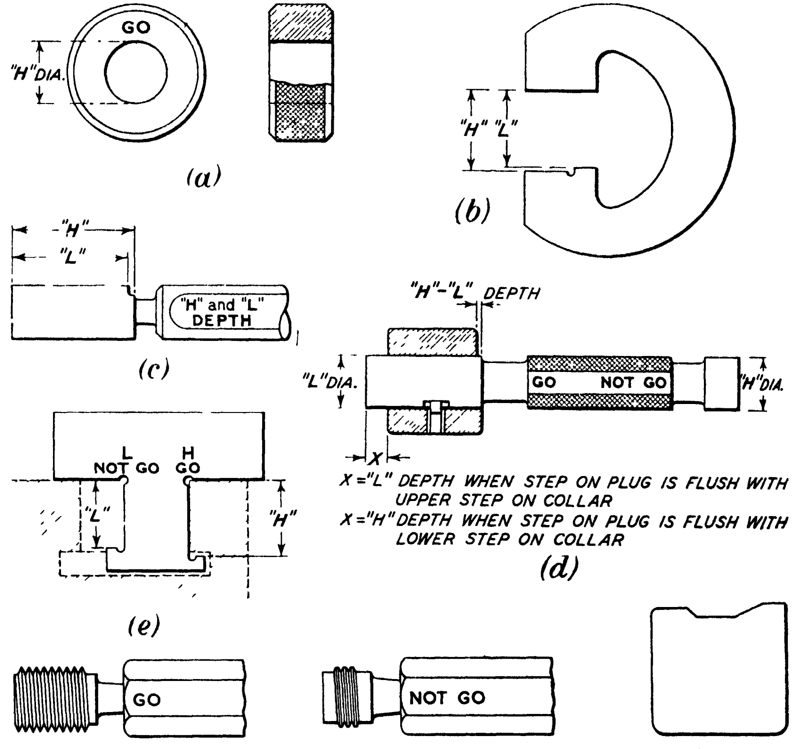

GO
"H" DIA.
(a)
"H"
"L"
(b)
"H"
"L"
"H" and "L" DEPTH
(c)
"H"-"L" DEPTH
"L" DIA.
GO
NOT GO
"H" DIA.
X
X="L" DEPTH WHEN STEP ON PLUG IS FLUSH WITH UPPER STEP ON COLLAR
X="H" DEPTH WHEN STEP ON PLUG IS FLUSH WITH LOWER STEP ON COLLAR
(d)
L
H
NOT GO
GO
"L"
"H"
(e)
GO
NOT GO
(f)
(g)
(h)

Fig. 16.4. (*a*) "Go" plain ring gauge. (*b*) "Go" and "Not Go" gap gauge. (*c*) Depth gauge incorporating "H" and "L" gauging step. (*d*) Sliding collar depth gauge. (*e*) Plate depth gauge. (*f*) "Go" full form screw plug gauge. (*g*) "Not Go" effective diameter plug gauge. (*h*) Profile gauge

DEPTH GAUGES are of various types. Fig. 16.4*c* shows a depth gauge which may also be used as a "Go" gauge for the internal diameter of a hole in a component. The depth is controlled by two steps formed at distances, from the leading end of the plug gauge, equal to the H. and L. limits of depth respectively. When the gauge is inserted in the hole the end face of the hole should lie between the two steps on the gauge.

A somewhat similar gauge (Fig. 16.4*d*), used for inspecting the depths of recessed holes, has a sliding collar, the upper surface of which may easily be seen. This surface has two steps which control the depth of the hole in the same way as the previous gauge.

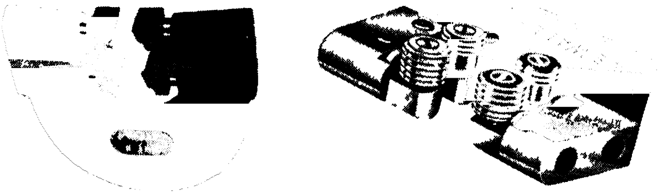


Fig. 16.5. (*Left*) Wickman type thread calliper gauge; (*right*) roller type thread calliper gauge

(*Newall Engineering Co. Ltd.*)

Fig. 16.4*e* shows a plate depth-gauge used to control the distance from the undercut at the base of a tapped hole to the plane containing the open end of the hole.

SCREW GAUGES are seen in Figs. 16.4*f* and *g*. Thread *calliper gauges* (Fig. 16.5) are frequently used instead of screw ring gauges. They resemble "Go" and "Not Go" adjustable plain gap gauges in shape but have threaded anvils, and may be either of the *Wickman* type, with anvils of a special shape, or of the *roller* type.

The "Go" anvils are of full form in either case and have a length of thread at least equal to the length of engagement of the threaded components. The "Not Go" anvils control the effective diameter only, are of a length of thread of two or three pitches, and have a thread form somewhat similar to that of "Not Go" effective diameter screw plug and ring gauges.

Thread calliper gauges are adjusted to size on special threaded setting plugs made to the H. and L. limits of size.

PROFILE GAUGES, Fig. 16.4*h*, are generally made of flat plate, one edge of which is made to the basic profile with which the component profile may be compared against an illuminated background. Feelers may be used to estimate the size of any gap which may occur between the two profiles, if this is of sufficient size (say

0·002 in.), but discrepancies of very much smaller value can be clearly detected by eye.

Taper Gauges are mostly designed to control a toleranced diameter at one end of the taper on the component, and also to exercise some measure of control over the rate of taper. The accuracy of taper of the component is verified in the case of the taper plug, and ring gauge, Figs. 16.6*a* and *b*, by endeavouring to rock the gauge on the component when the two are assembled together. Additional information about the fit of the gauge and component may be obtained by the use of a suitable marking agent, such as prussian blue. If the toleranced diameter of the component at one end of the taper is between its allowable limits, then this end should fall between the H. and L. steps of the gauge when the component and gauge are assembled together.

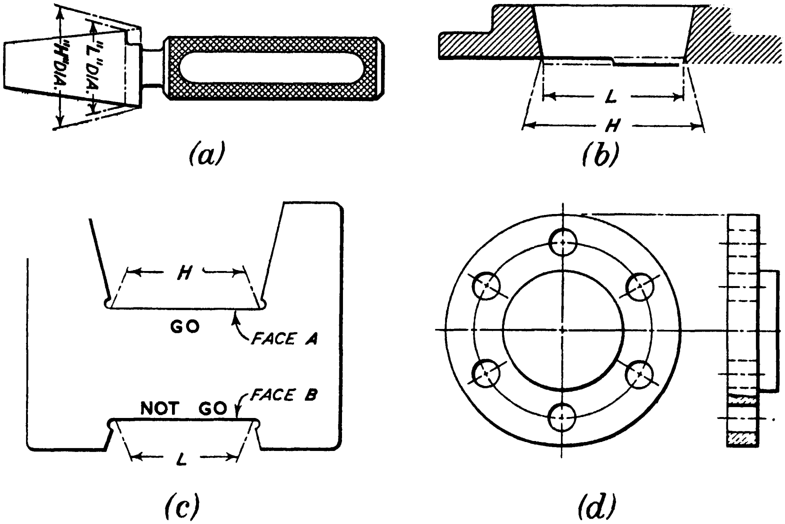


Fig. 16.6. (*a*) Taper plug gauge with gauging steps. (*b*) Taper ring gauge with gauging steps. (*c*) "Go" and "Not Go" taper plate gauge. (*d*) Simple type of position gauge

Fig. 16.6*c* is a "Go" and "Not Go" taper plate gauge for controlling external taper. The rate of taper of the component is inspected by comparing the fit of the "Go" gauge and component against an illuminated background; if the diameter at the end of the component taper is between its allowable limits then the end of the component should contact face A when inserted in the "Go" gap, and should not contact face B when inserted in the "Not Go" gap.

Position Gauges are of many diverse types and are, as their name implies, used to check the relative positions of certain component features such as pins or holes. Fig. 16.6*d* shows a gauge used for inspecting the positions of the studs on a flange; the gauge should assemble completely with the flange if the studs on the latter are within the allowable limits for size and position.

Measurement of Limit Gauges. Before any dimensional measurements of a limit gauge are made it is best to make a preliminary inspection of the general, or non-gauging, dimensions of the gauge, and also of the hardness, flatness, and straightness of the gauging surfaces. The checking of the *general dimensions* takes little time, and may reveal errors which prevent the correct functioning of the gauge.

The *hardness* of the gauging surfaces may usually be measured on a hardness-testing machine, preferably of the diamond pyramid type. A difficulty arises, however, with certain types, such as plain and screw ring gauges, as it may not be possible to apply the diamond indentation point to the gauging surfaces; and in such cases the hardness should be estimated by means of a scratch test. A scratch made on the gauging surface by a suitable scriber is compared with a similar scratch on a block of steel of known hardness. A series of such blocks should be provided, ranging in hardness from 450 D.P.N. to 850 D.P.N. (D.P.N. – "Diamond Pyramid Number"), and the hardness of the gauge may then be assumed to be the hardness of the block on which a similar scratch may be made. A suitable scriber consists of a small rat-tail file which is mounted in a wooden handle, and has a radius of approximately 0·025 in. ground at one end. It is essential to use the same pressure on the scriber when making the scratches on the gauge and blocks, and, if this precaution is taken, hardness values may be estimated to within 50 points on the D.P.N. scale.

The *flatness* and *straightness* of gauging surfaces may be checked accurately and quickly by applying a knife-edged straightedge to the surface, and viewing any gap between the two against an illuminated background. Under favourable conditions it is possible to see a gap of light as small as 0·00003 in. Substantial errors of flatness may produce a gap of light exceeding 0·0003 in. in magnitude, and the estimation of the size of such a gap is not possible with any degree of accuracy. In these cases slip-gauges of different sizes should be introduced between the gauging surface and the straight-edge, so as to reduce the gap of light to a value which can be accurately estimated. If this is not convenient the gauging surface should be set up horizontally on a surface-plate, and the flatness or straightness checked by means of a sensitive dial indicator mounted on a stand which is placed on the surface-plate.

Having completed the preliminary inspection of the gauges the measurement of the gauging dimensions may be undertaken, and this is described for different types of gauges.

PARALLEL GAP GAUGES may be measured directly by means of *slip gauges*, or combinations of *slip-gauges* and *length-bars*, depending on whether the gap is smaller or larger than about 5 in. The slip-gauge or length-bar combination should be laid on its side on a surface-plate, with its end faces vertical; the gap gauge should be supported lightly at both ends and lowered over the slip-gauge combination so that only its own weight allows it to move downwards; and the slip-gauge combination should be gradually increased until the gap gauge just nips the slip combination, and yet moves freely over a combination which is 0·0001 in. smaller in size. The size of the gap gauge is then equal to the mean size of the "Go" and "Not Go" slip piles so obtained. In order to detect errors in parallelism of the gauging surfaces of the gap it is of importance to present both sides of the gauge to the slip-gauge combination. Small gap gauges may be measured to an accuracy of ±0·00005 in. by the above method, but the accuracy of measurement of larger gap gauges is not so great, due to the possible springing open of the jaws when inserting the slip-gauge combination, and any temperature differences which may occur between the gap gauge and slip-gauges.

PLAIN PLUG GAUGES may be measured by a *hand micrometer* to an accuracy of ± 0·0001 in. For such measurements the micrometer should be used as a comparator, i.e. by taking successive readings on a standard of known size and on the gauge, and then adding or subtracting the difference between the readings in relation to the size of the standard. The standard size should approximate to the size of the plug gauge, so that the travel of the micrometer spindle during the measurement is small enough to minimize the effect of any progressive pitch errors of the micrometer screw. The standard should preferably be a plain plug, and not a slip-gauge combination, to lessen the effect of any possible errors of parallelism of the micrometer anvil and spindle faces, and any compression effects caused by the measuring force on the gauge and standard.

If the tolerance on the plug gauge is appreciably less than 0 001 in. it is necessary to use a more accurate method of measurement and a

bench micrometer, diameter-measuring machine, or a ***high-magnification dial comparator*** should be employed. The previous remarks on the use of the hand micrometer as a comparator apply also to the use of a bench micrometer or diameter-measuring machine. High-magnification dial comparators can only measure over a limited range of size at any one setting, and the size of the standard has to approximate very closely to that of the gauge; slip-gauge combinations are therefore used as setting standards for comparators. The measuring forces of dial comparators are very small, and errors caused by the different compression effects on the flat surface of the slip-gauges and the radiused gauge surface may be neglected. An advantage of the use of slip-gauge standards for dial comparators is that the size of the standard may be made equal to one of the limits of size of the plug gauge, and hence the effect of any errors of the comparator scale graduations is minimized.

When measuring the plug gauge sufficient readings should be taken to ascertain the presence or otherwise of any ovality or taper of the gauging surface. It may be necessary also to check the gauge for "lobing", by rotating it, in a suitable angle block, beneath a dial gauge of high sensitivity, or in some other suitable manner.

A reading on the standard should be taken after the plug gauge has been measured, to make sure the instrument setting has not altered during the measurements; *this rule should be followed when using all types of measuring instruments.*

CYLINDRICAL RING GAUGES below ½ in. diameter are difficult to measure accurately, and it may be best to measure the *approximate* size of the gauge by suitable plugs, and then to insert a *mandrel* having a mean size equal to the measured approximate size and a taper of 0·0002 in. on diameter per inch of length; the size of the ring gauge is then given by the size of the mandrel where it fits the gauge. The measurement of ring gauges by cylindrical plugs or tapered mandrels gives the minimum size of the gauge, and so the presence of any ovality is not checked; but it may be measured by setting the gauge concentrically on the face-plate of a dividing head and inspecting the bore of the gauge with a sensitive dial indicator. Care should be exercised when inserting a tapered mandrel in a gauge, as, due to the small rate of taper, it is possible to apply a considerable *wedging* force on the gauge.

The sizes of ring gauges having diameters greater than ½ in. may be obtained by measuring with slip-gauges the distance between two small equal-sized rollers or balls placed diametrically opposite in the ring gauge. A slip-gauge combination is found which is just nipped by the rollers while a combination 0·0001 in. smaller enters between the rollers by virtue of its own weight; the diameter of the ring gauge is then calculated by adding the mean size of the two slip-gauge combinations to the sum of the diameters of the rollers. By using rollers, the size of the gauge may be estimated to ±0·00005 in. for gauges up to 4 in. diameter; an increased accuracy of measurement may be obtained by the use of balls although more skill is required in their use.

Cylindrical ring gauges may be measured on most types of horizontal comparator, and ovality and taper of the gauges may be quickly investigated; an accuracy of measurement of ±0·00005 in. is normally attainable by using such comparators.

FORM OR PROFILE GAUGES are most conveniently inspected by *optical projection* at a standard magnification and comparison of the projected shadow image with a standard projection diagram. The standard magnification most generally used is 50. Another standard magnification used is 100, but, due to the reduced intensity of illumination at the projector screen and the consequent loss of definition of the image, the possible accuracy of measurement at this magnification is not much greater than at 50.

The magnified diagram with which the form is compared should be drawn on a material which has a good drawing surface and is also dimensionally stable. Metal sheets spray-painted with white cellulose are particularly suitable for opaque screen projectors, and may be used many times if the diagrams are drawn in Indian ink or water colour, which may be sponged off after use.

Form gauges may also be measured on a *toolmaker's microscope*, especially when the separate tolerancing of the individual dimensions of the form makes the production of an enlarged projection diagram difficult. A toolmaker's microscope is also useful for measuring form gauges which are too large to be projected at the required magnification.

HEIGHT AND DEPTH GAUGES may be measured by means of *depth micrometers*, *bench micrometers* or *comparators*. The "gap of light" method is to be recommended (Fig. 16.7*a*). The gauge is placed on a surface-plate in front of a light, and slip-gauges are built up until the top of the slip-gauge combination and the gauging surface of the gauge are the same height above the surface-plate, when no gap of light is visible below a knife-edged straight-edge resting simultaneously on the two.

Alternatively a *sensitive dial gauge*, mounted on a stand on the surface-plate, may be employed to measure the difference in height of the gauge and the slip-gauge combination. This difference should not exceed 0·0005 in. for the greatest accuracy of measurement, or errors in the dial gauge scale graduations may have a detrimental effect on the accuracy of the measurement.

TAPER PLUG GAUGES may be inspected in the following way. The gauge is mounted vertically on a surface-plate with the small-diameter end of the gauge downwards, and measurements are made across two equal-sized precision rollers, which are supported on equal slip piles which may be altered so that the rollers contact the taper in various planes normal to the axis of the taper. The process is facilitated by the use of a taper-measuring machine, which is standardized by taking measurements across the rollers on a standard cylindrical plug. Ovality may be checked by taking diametral measurements around the circumference of the taper plug in each measuring plane, and the uniformity of the rate of taper is checked by taking measurements in three or more planes uniformly spaced and normal to the axis of the taper. The diameter of the small end of the gauge is then calculated from the formula given in Fig. 16.7*b*.

TAPER RING GAUGES above $\frac{3}{4}$ in. diameter may be measured in a similar way to taper plug gauges. The ring gauge is mounted on a surface-plate with the axis of the taper vertical and the small diameter end uppermost. Measurements are made by means of slip-gauge combinations between two precision balls of equal size supported on equal slip piles placed on the surface-plate. The measurements are made in planes at different heights from the base of the gauge, the same criterion of fit being used as for cylindrical ring gauges. The diameter of the large end of the gauge is then calculated from the formula given in Fig. 16.7*c*.

Taper ring gauges of sizes below $\frac{3}{4}$ in. diameter are best measured by inserting precision balls of various sizes in the gauge and measuring the distance (stand off) between the top of each ball and one of the end faces of the gauge. The diameter in the plane of one end face is then calculated from the formula given in Fig. 16.7*d*.

TAPER PLATE GAUGES are measured by the methods described for taper plug and ring gauges, depending whether the taper is external or internal. In the latter case it is usually more convenient to use precision rollers in place of balls.

PARALLEL SCREW PLUG GAUGES. The various elements* of a

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* Refer to definitions on page 408.

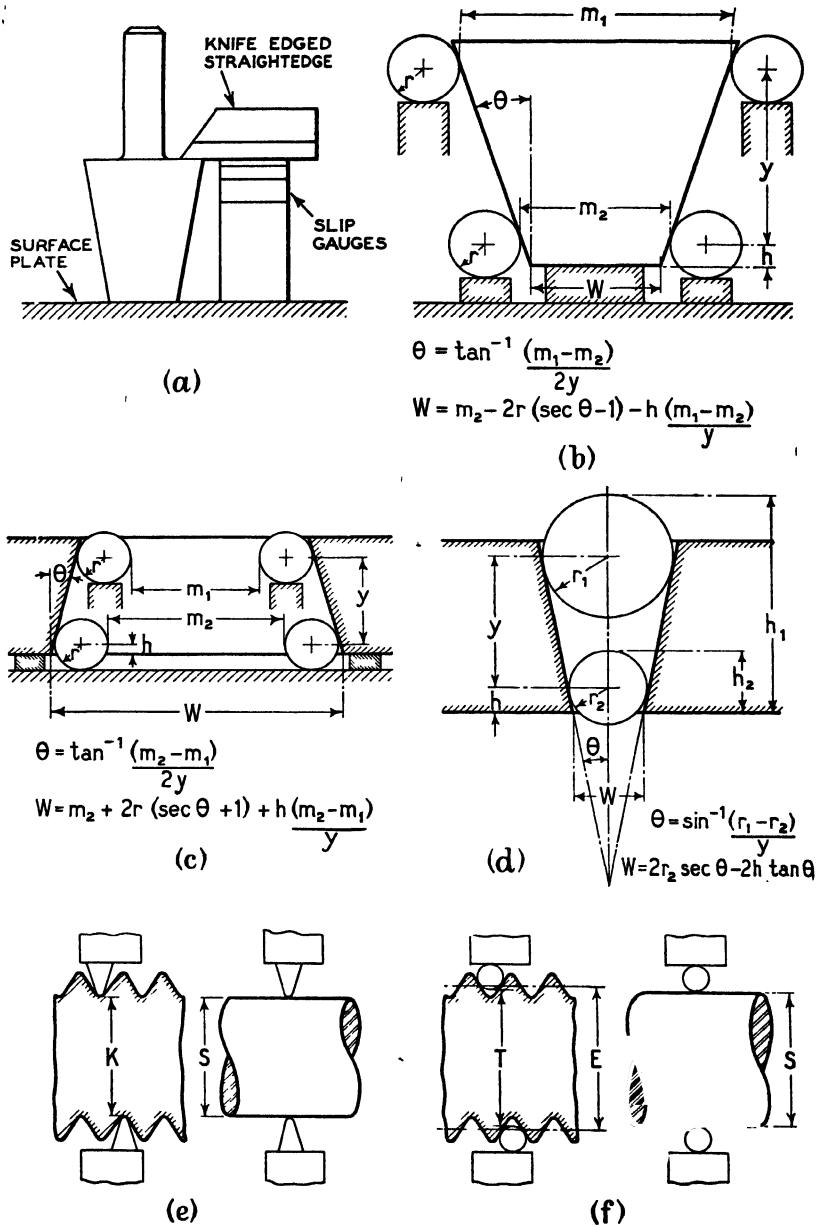
KNIFE EDGED STRAIGHTEDGE
SLIP GAUGES
SURFACE PLATE
(a)
m_1
r
θ
y
m_2
h
W
$\theta = \tan^{-1} \frac{(m_1 - m_2)}{2y}$
$W = m_2 - 2r(\sec\theta - 1) - h\frac{(m_1 - m_2)}{y}$
(b)
θ
r
m_1
m_2
y
h
W
$\theta = \tan^{-1} \frac{(m_2 - m_1)}{2y}$
$W = m_2 + 2r(\sec\theta + 1) + h\frac{(m_2 - m_1)}{y}$
(c)
r_1
y
h_1
h_2
h
r_2
θ
W
$\theta = \sin^{-1} \frac{(r_1 - r_2)}{y}$
$W = 2r_2 \sec\theta - 2h\tan\theta$
(d)
K
S
(e)
T
E
S
(f)

Fig. 16.7. (*a*) Measuring heights by "gap of light" method. (*b*) Measurement of taper plug gauge. (*c*) Measurement of taper ring gauge. (*d*) Measurement of small taper ring gauge. (*e*) Measurement of minor diameter of screw plug gauge. (*f*) Measurement of effective diameter of screw plug gauge screw plug gauge are measured in the following way. *The Major Diameter* is measured on a diameter-measuring machine which is standardized in a similar way to a bench micrometer for this purpose. *The Minor Diameter* is obtained by making measurements on a diameter-measuring machine between the apices of vee pieces placed in the thread groove on opposite sides of the gauge. These vee pieces have a radius at the apex which is smaller than the root radius of the thread, so that during the minor diameter measurement they contact the root of the thread. The diameter-measuring machine is standardized for these minor diameter measurements by taking readings on a cylindrical plug standard of known size S with the vee-pieces in position on both sides of the standard (Fig. 16.7*e*). The standard is now replaced by the gauge and a series of readings is taken on the minor diameter. The minor diameter K of the gauge will be equal to the known diameter of the standard plus or minus the difference between the readings taken on the gauge and the standard respectively.

The Effective Diameter is obtained from measurements T (Fig. 16.7*f*) under a pair of thread-measuring cylinders placed in the thread groove on opposite sides of the gauge. A diameter-measuring machine is used for this purpose, standardized as for minor diameter measurements but with the thread-measuring cylinders in position on both sides of the standard S. The effective diameter is then calculated from the formula

$$E = T + P - c + \text{compression correction},$$

where T is the measured diameter under the cylinders, P is a constant depending on the pitch and angle of the thread and the diameter of the cylinders, c is a correction for the rake of the thread,* and the compression correction is for the compression of the cylinders caused by the measuring force of the machine. The rake and compression corrections for standard series of screw threads are usually very small and tend to cancel out, but, due to the small tolerances on screw gauges, they must not be neglected.

The *Pitch* is measured on a pitch-measuring machine, and the *thread form*, including crest and root radii and flank angles, is examined by optical projection at a standard magnification.

PARALLEL SCREW RING GAUGES are best inspected by *plug check gauges*. The minimum number of check gauges required is four, namely: a "Go" *full-form screw plug check gauge* made to the low limit of the screw ring gauge, a "Not Go" *effective diameter screw plug check gauge* having threads cleared at the crests and roots and made to the upper limit of the screw ring gauge, and "Go" and "Not Go" *minor diameter plain plug check gauges,* made respectively to the lower and upper minor diameter limits of the screw ring gauge.

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* *Notes on Applied Science, No. 1: Gauging and Measuring Screw Threads.* H.M.S.O.

In addition to this inspection it is usual to measure the *pitch* of the ring gauge on a pitch-measuring machine, and to inspect the *thread form* and measure the *flank angles* by optical projection of a cast made of plaster of paris or a mixture of sulphur and graphite; for small ring gauges a cast of dental wax may be used.

The inspection of screw ring gauges by plug check gauges verifies that the ring gauges lie between their limits of size. If the actual effective diameters of the screw ring gauges are required a suitable horizontal comparator is necessary, employing two styluses which seat in the thread groove on opposite sides of the gauge.

The major diameters of screw ring gauges are not usually measured, but inspection of the thread form provides an indirect verification by the checking of the depth of the thread.

Check Gauges are very useful in inspecting *limit gauges,* particularly large numbers of them.

"Go" and "Not Go" *flat slip* or *cylindrical plug gauges* are very useful for inspecting *small gap* or *cylindrical ring gauges.*

Large form gauges may be inspected by comparison with the mating form of a check gauge against an illuminated background.

Taper ring and *gap gauges* may be inspected by suitable *taper plug* or *plate check gauges,* and it is often possible to estimate the size of the taper gauge by the relative position of the check gauge when seated in the limit gauge.

POSITION GAUGES generally require the use of a suitable *dividing-head* or *universal measuring block* for their measurement, and this may be facilitated by the provision of mandrels for fitting in any holes in the gauges. The design of position gauges varies so much that it is difficult to lay down any procedure for their measurement.*

Screw Threads. The majority of screw threads for fastening purposes have some type of symmetrical vee-thread, Fig. 16.8*a*. The *Whitworth* form of thread, having a 55° angle between the flanks of the vee and equal radii at the crest and root, is used extensively in Great Britain for screw threads above $\frac{1}{4}$ in. diameter.

For smaller sizes the *British Association* (*B.A.*) form of thread having a 47½° angle between the flanks of the vee is used. The larger root radius and slightly smaller depth of this thread form facilitate the manufacture of small diameter threads.

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* *Notes on the Use of Circular Dividing Apparatus for Angular and Linear Measurement,* H.M.S.O.

The *Metric*, or *Système Internationale* (*S.I.*), form of thread is used mainly on the Continent. This has a 60° angle between the flanks of the vee and a flat crest and root; in practice the root is generally radiused so as to clear the flat crest of the mating thread.

The *Unified* form of thread has been agreed as a common standard between the U.S.A., Great Britain and Canada, and it is being used increasingly in this country. It has a 60° angle between the flanks.

A number of special threads are widely used, and among these may be mentioned the *square* and *Acme* threads, which are used for purposes such as traversing slide rests on lathes, and the *Buttress* thread, which is used for withstanding large axial loads in one direction only.

The standardization of suitable combinations of diameters and numbers of threads per inch for screw threads, as well as the establishment of limits and tolerances, has received much attention in this country and the following British Standards have been published:

1. B.S. 84 : 1956. *Screw Threads of Whitworth Form.*

This Standard provides a coarse and a fine series of threads, the *British Standard Whitworth* (*B.S.W.*), and the *British Standard Fine* (*B.S.F.*), series respectively:

2. B.S. 1580 : 1953. *Unified Screw Threads.*

This Standard provides a coarse and a fine series of threads, the *Unified Coarse* (*UNC*), and the *Unified Fine* (*UNF*) series respectively.

3. B.S. 93 : 1951. *British Association Screw Threads.*
4. B.S. 1095 : 1942. *Metric Screw Threads.*

Three classes of tolerance of bolts and three classes of nuts are given in the Whitworth, Unified and Metric thread Standards. In the Whitworth and Unified Standards provision is made in certain cases for a minimum clearance (allowance) between the maximum allowable size of an external thread, and the minimum allowable size of the corresponding internal thread.

In addition to the standard series of threads given in the Whitworth, Unified and Metric Standards, recommended tolerances are also given for various non-standard combinations of diameters

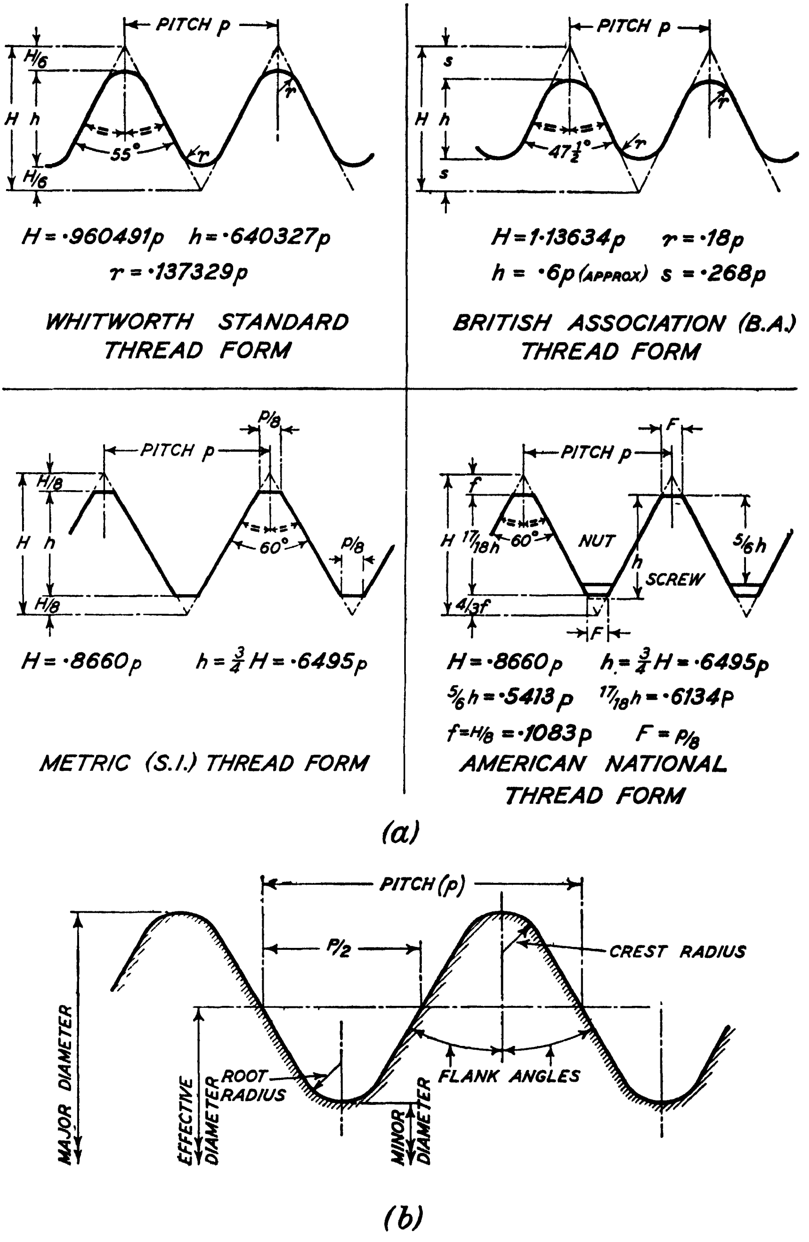


Fig. 16.8. (*a*) Standard thread forms (*b*) Elements of a screw thread

and numbers of threads per inch, for use in design work—as distinct from nuts and bolts.

ELEMENTS OF SCREW THREADS. The successful inspection of screw threads entails the verification of certain dimensions, or "elements," of the threads. These elements (Fig. 16.8*b*) may be defined as follows:

1. *The Crest* is the prominent part of a thread, whether the thread be external or internal.

2. *The Root* is the bottom of the groove between the flanking surfaces of the thread, whether the thread be external or internal.

3. *The Flanks* are the straight sides which connect the crest and root.

4. *The Flank Angles* are the angles between the individual flanks and the normal to the axis of the thread, measured in an axial plane section.

5. *The Major Diameter* of a parallel thread is the diameter measured, normal to the axis, over the crests of an external thread or to the roots of an internal thread.

6. *The Minor Diameter* of a parallel thread is the diameter measured, normal to the axis, to the roots of an external thread or to the crests of an internal thread.

7. *The Pitch* is the distance, measured parallel to the thread axis, between corresponding points on adjacent thread forms in the same axial plane section and on the same side of the axis.

8. *The Effective Diameter* is the diameter of an imaginary co-axial cylinder which intersects the thread form in such a manner that the intercept on a generator of the cylinder, between the points where it meets the opposite flanks of the thread groove, is equal to half the basic pitch.

MATING THREADS, when assembled together, contact on their flanks, and there is a clearance at their major and minor diameters except in the rare instance when both external and internal threads are on their maximum metal limits. Hence the effective diameter, flank angles, and pitch are the most important elements, because they control the fit of the assembled threads. Now consider a bolt thread having flank angle errors of $+\ \delta\theta$ or $-\ \delta\theta$ (Fig. 16.9*a*). If this screw thread were an exact fit in a nut having a perfect thread form, then, the effective diameter of the nut would have to be larger than that of the bolt by an amount equal to twice the maximum radial excess metal *ab* on the flank of the bolt thread form. It should be noted that the effective diameter of the nut is independent of the algebraic sign of the flank angle error of the bolt. The effective diameter of this *perfect nut* is termed the *virtual* effective diameter of the *bolt*. Conversely, it may be shown that if a nut has flank angle errors, then, the effective diameter of the perfect bolt which just fits the nut will have to be *smaller* than that of the latter by twice the maximum radial excess metal on the flank of the nut thread form. The effective diameter of this *perfect bolt* is termed the *virtual* effective diameter of the *nut*. Therefore, flank angle errors, irrespective of their sign, result in the virtual effective diameters of bolts and nuts having values larger and smaller respectively than their simple effective diameters.

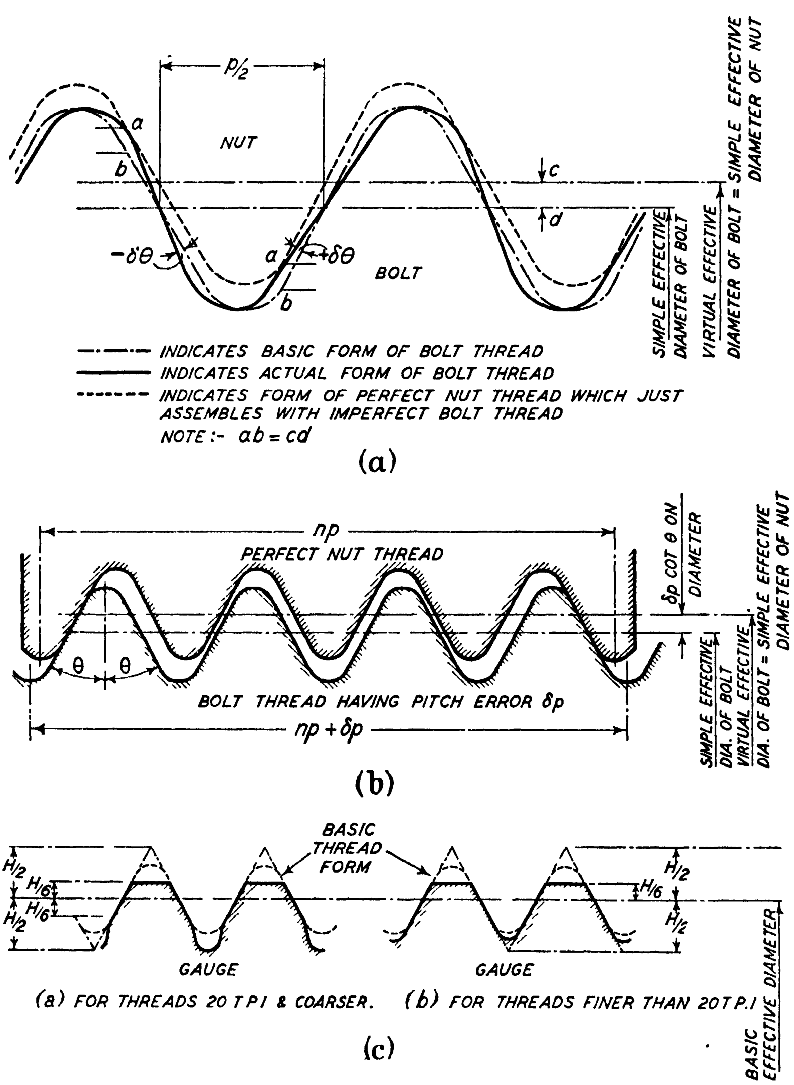
The effect of pitch errors of screw threads is somewhat similar to that of angle errors. Consider, for example, a bolt screw thread having a pitch error of δp over the length of engagement of the nut (Fig. 16.9*b*). The *simple* effective diameter of a *nut* having a perfect thread form which will just fit the *bolt* thread is greater than the simple effective diameter of the bolt by an amount $\delta p \cot \theta$, where θ is the flank angle of the thread. The *virtual* effective diameter of the bolt is therefore *greater* than its simple effective diameter by an amount $\delta p \cot \theta$. Similarly, it may be shown that the *virtual* effective diameter of a nut having pitch errors δp is *smaller* than its simple effective diameter by a similar amount, $\delta p \cot \theta$.

It may be deduced by a development of the above methods that virtual effective diameters of bolts and nuts having flank angle *and* pitch errors are greater or less respectively than their simple effective diameters by the effective diameter equivalents of the flank angle and pitch errors.

It is usual to give tolerances on the major, effective, and minor diameters *only* in British Standards for screw threads on components. In order that assembly of mating screw threads can be guaranteed it is essential, therefore, that the virtual effective diameters as well as the simple effective diameters of the screw threads shall be within the specified effective diameter limits, and any gauging system which controls the sizes of the screw threads must take this into account.

A Gauging System for External Screw Threads comprises the following:

1. A "Go" *screw ring* or *calliper gauge* which is made to the H. limit of the work, has the full form of thread, and a length of thread at least equal to the maximum length of engagement of the threads on the mating components. This gauge ensures that the major, simple effective, virtual effective, and minor diameters of


P/2
NUT
a
b
c
d
-δθ
a
+δθ
b
BOLT
SIMPLE EFFECTIVE DIAMETER OF BOLT
VIRTUAL EFFECTIVE DIAMETER OF BOLT = SIMPLE EFFECTIVE DIAMETER OF NUT
—·—·— INDICATES BASIC FORM OF BOLT THREAD
——— INDICATES ACTUAL FORM OF BOLT THREAD
------ INDICATES FORM OF PERFECT NUT THREAD WHICH JUST ASSEMBLES WITH IMPERFECT BOLT THREAD
NOTE :- ab = cd
np
PERFECT NUT THREAD
θ
θ
BOLT THREAD HAVING PITCH ERROR δp
np + δp
δp COT θ ON DIAMETER
SIMPLE EFFECTIVE DIA. OF BOLT
VIRTUAL EFFECTIVE DIA. OF BOLT = SIMPLE EFFECTIVE DIAMETER OF NUT
BASIC THREAD FORM
H/2
H/6
H/6
H/2
GAUGE
GAUGE
(a) FOR THREADS 20 TPI & COARSER.
(b) FOR THREADS FINER THAN 20 T.P.I
H/2
H/6
H/2
BASIC EFFECTIVE DIAMETER

(a)

(b)

(c)

Fig. 16.9. (*a*) Effect of angle errors on assembly of screw threads. (*b*) Effect of pitch errors on assembly of screw threads. (*c*) Thread forms of effective diameter gauges the component thread are nowhere greater than the specified H. limit.

2. A "Not Go" *screw ring* or *calliper gauge* which is made to the L. limit of the component effective diameter, and ensures that the simple effective diameter of the component thread is nowhere smaller than the specified L. limit. For this purpose the threads on the gauge are cleared at the crests and the roots (Fig. 16.9*c*), so that the gauge contacts the component threads on the middle part of the flanks. In addition, the number of threads is limited to two or three. The localized contact of the gauge with the flanks of the component thread reduces to a minimum the effect of any flank angle errors of the latter on the function of the gauge. Likewise, the small number of threads minimizes the effect of any pitch errors of the component thread. The gauge, therefore, does control the simple and not the virtual effective diameter of the work.

3. A "Not Go" *plain gap gauge* which is made to the L. limit of the major diameter of the component thread, and ensures that the latter is nowhere smaller than the specified limit.

It will be noted that the L. limit of the minor diameter of the external thread on a component is not usually checked with gauges; it is controlled by the use of screwcutting or forming tools having a suitable crest radius.

A Gauging System for Internal Screw Threads follows the same general principles as for external threads. It comprises:

1. A "Go" *screw plug gauge*, made to the L. limit of the work, and having the full form of thread of a length at least equal to the maximum length of engagement of the threads on the mating components.

2. A "Not Go" *effective diameter screw plug gauge*, made to the H. limit of the component effective diameter, and having a thread form cleared at the crests and roots and of a length of two or three pitches.

3. A "Not Go" *plain plug gauge* made to the H. limit of the component minor diameter.

The H. limit of the major diameter of an internal component thread is not usually controlled by gauging, but by the use of screw forming tools having a suitable crest form with respect to their effective diameters.

Multi-gauging Machines usually incorporate a number of similar indicating units which are suitably arranged so that all the required dimensions are gauged at once. In certain cases they inspect components to predetermined limits, giving no indication of actual size but only whether the component is within or outside the allowable limits of size. Fig. 16.10 shows a Sigma Sorting Machine. Each of the indicating units operates one of the inbuilt lights when its contact surface touches the component. An amber light indicates that the dimension is above the upper limit, a green light shows it is between the limits, and a red light shows that it is below the lower limit. The operator can see at a glance whether the component is between limits, and the components are sorted into undersize, satisfactory, and oversize, the quantity being recorded for each category.

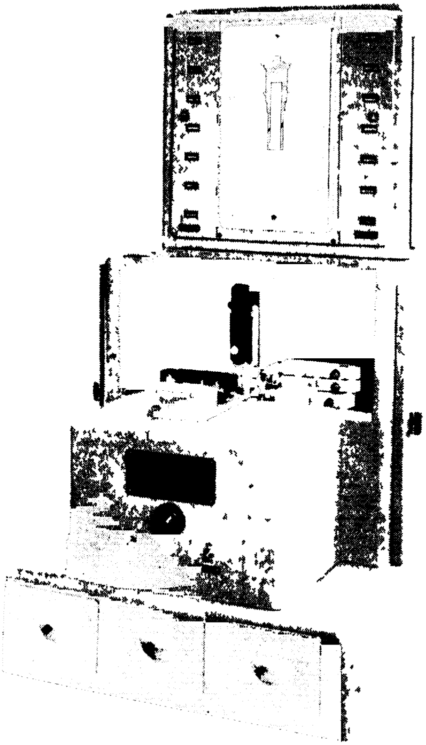


Fig. 16.10. Sorting machine

(*Sigma Instrument Co. Ltd.*)

For Bibliography see end of book.

CHAPTER XVII

PART 1: THE MEASUREMENT OF SURFACE TEXTURE

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Taylor Taylor and Hobson, Leicester

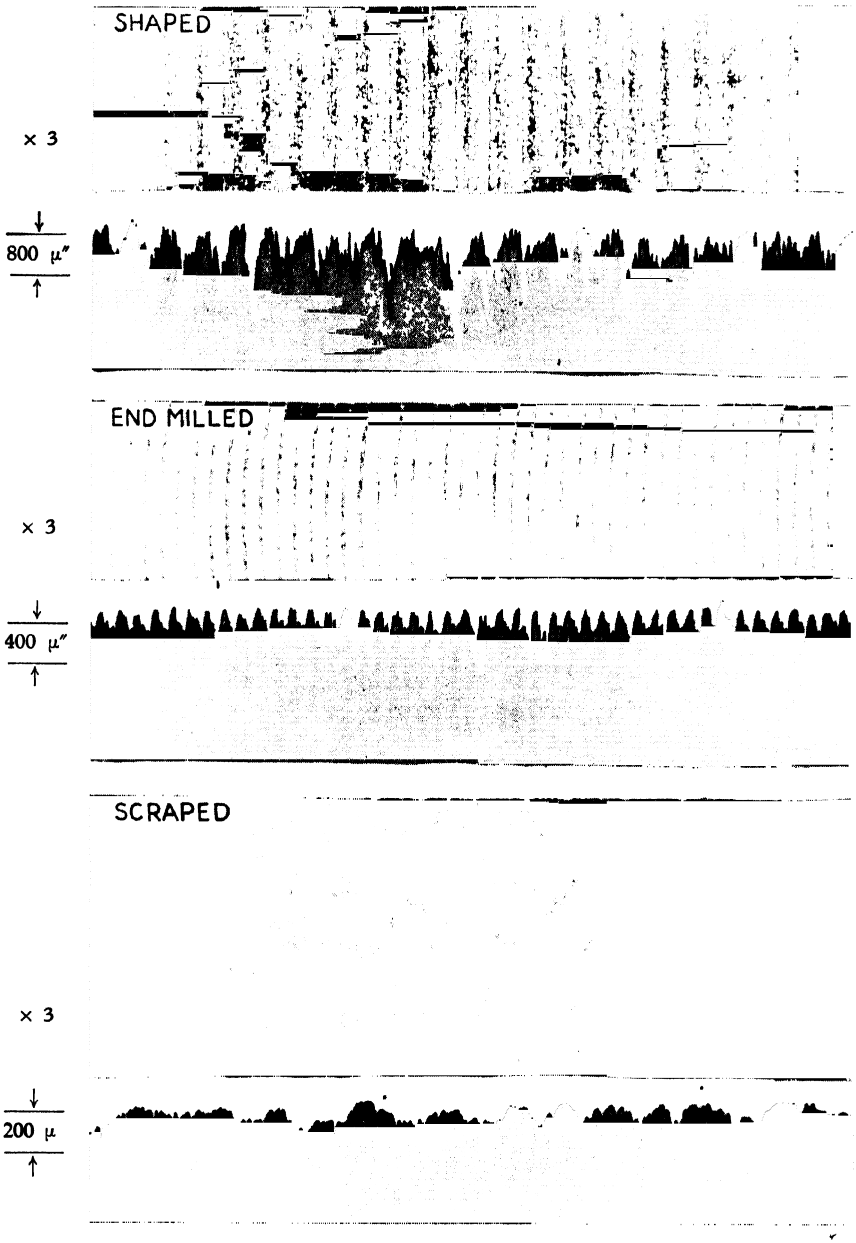
SURFACE texture is deemed to include all those irregularities which, recurring many times across the surface, tend to form on it a pattern or texture.

While the performance of surfaces from such points of view as lubrication, wear, corrosion, resistance to fatigue, is often affected by the texture, functional considerations may involve not only the geometrical character of the irregularities, but also the physical structure of the outer layers of the material, which structure, compared with that of the material in bulk, may be modified considerably by the manufacturing process. (Refs. 10, 15, 29–32.)

The surfaces whose quality may need to be controlled in one engineering context or another are found to cover a wide dimensional range, extending from those produced in the largest planing machines having a traverse feed of an inch or so, down to those produced by the finest lapping of which the scratch marks may be spaced but a few hundred thousandths of an inch apart. The peak-to-valley height of surface texture is found to be small compared with the spacing of the crests: it runs from a few thousandths down to a few millionths of an inch. Some typical surfaces are shown in Fig. 17.1, in which particular note should be taken of the magnifications used in each case.

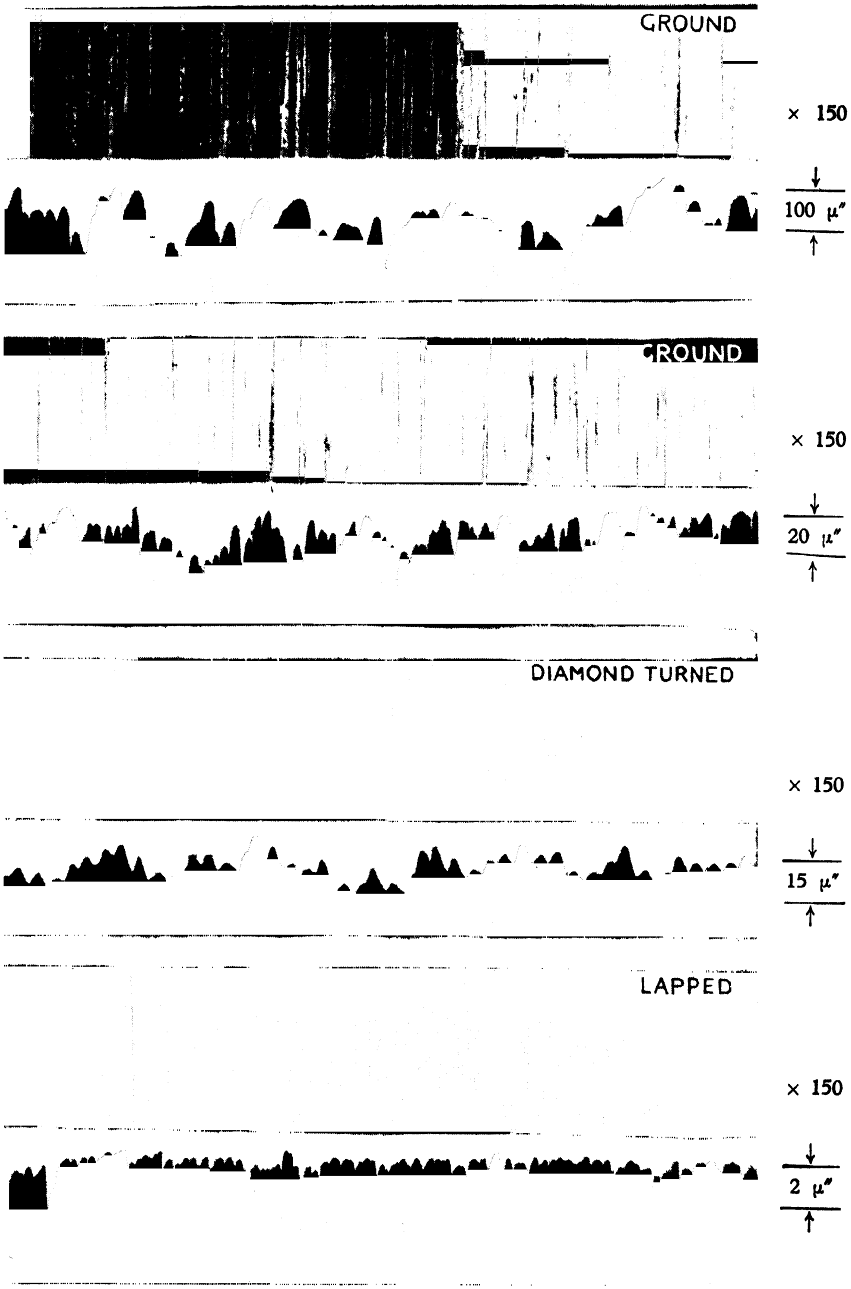
The photographs in Fig. 17.1 are plan views; they give an excellent idea of whether or not the pattern has directional qualities and tends to be repetitive, and often of the distance (or spacing) between successive crests; but they give no idea of the dimensions of the irregularities measured normally to the surface.

The graph shown beneath each of the photographs is a distorted end view of approximately the same part of the surface, the scale



(*a*)

Fig. 17.1. Photomicrographs showing plan view, and graphs showing cross-section (with exaggerated scale of height), of typical machined surfaces


GROUND
× 150
100 μ"
GROUND
× 150
20 μ"
DIAMOND TURNED
× 150
15 μ"
LAPPED
× 150
2 μ"

(*b*)

normal to the surface being very much greater than that along it. The employment of this form of distortion is generally unavoidable because of the small height of the irregularities compared with the separation of their crests. The amount of distortion is indicated by the ratio of the two figures given for the magnification, e.g. 3000/150, of which the first is the magnification normal to the surface and the second is the magnification along it. The slopes of the flanks of the irregularities are thus enormously exaggerated: they rarely lie at more than 5° to the general direction of the surface.

In principle, at least two cross-sections at right angles are needed to establish the topography of the surface, but in practice, when the irregularities to be portrayed are seen to have a marked sense of direction, a single cross-section approximately at right angles to their length will often suffice.

The irregularities produced by machining processes are of four main kinds. Firstly, within each tool mark or abrasive scratch mark, however narrow, irregularities can be found which result from the way in which the metal has been torn or otherwise detached from the surface; these might be called rupture or fragmentation marks. Secondly, there are the tool or scratch marks themselves, from the appearance of which the process is most commonly identified. Thirdly, there are irregularities arising from defects in the process such as vibration between the tool and work (chatter marks) or imperfect truing of a grinding wheel or setting of a milling cutter. Fourthly there are general errors of form resulting for example from imperfect slideways.

Those irregularities which are a natural and inevitable consequence of the process as carried out in a substantially perfect machine (those of the first and second kinds) are defined as Primary Texture* in the British Standard B.S. 1134 : 1950, and would generally be classed as Roughness in the American Standard B–46/55–1 Those irregularities which should theoretically not occur (the third kind) are defined as Secondary Texture* in B.S. 1134 : 1950 and would generally be classed as Waviness in B–46. Errors of form are generally deemed to lie outside the field of Surface Texture.

When the directions of the constituent patterns are inclined to each other, the presence of each is generally obvious from the appearance of the surface, but when a profile graph alone is available, it may be necessary to know something of the process used and its

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* These terms are being reconsidered with a view to securing uniformity with American terminology.

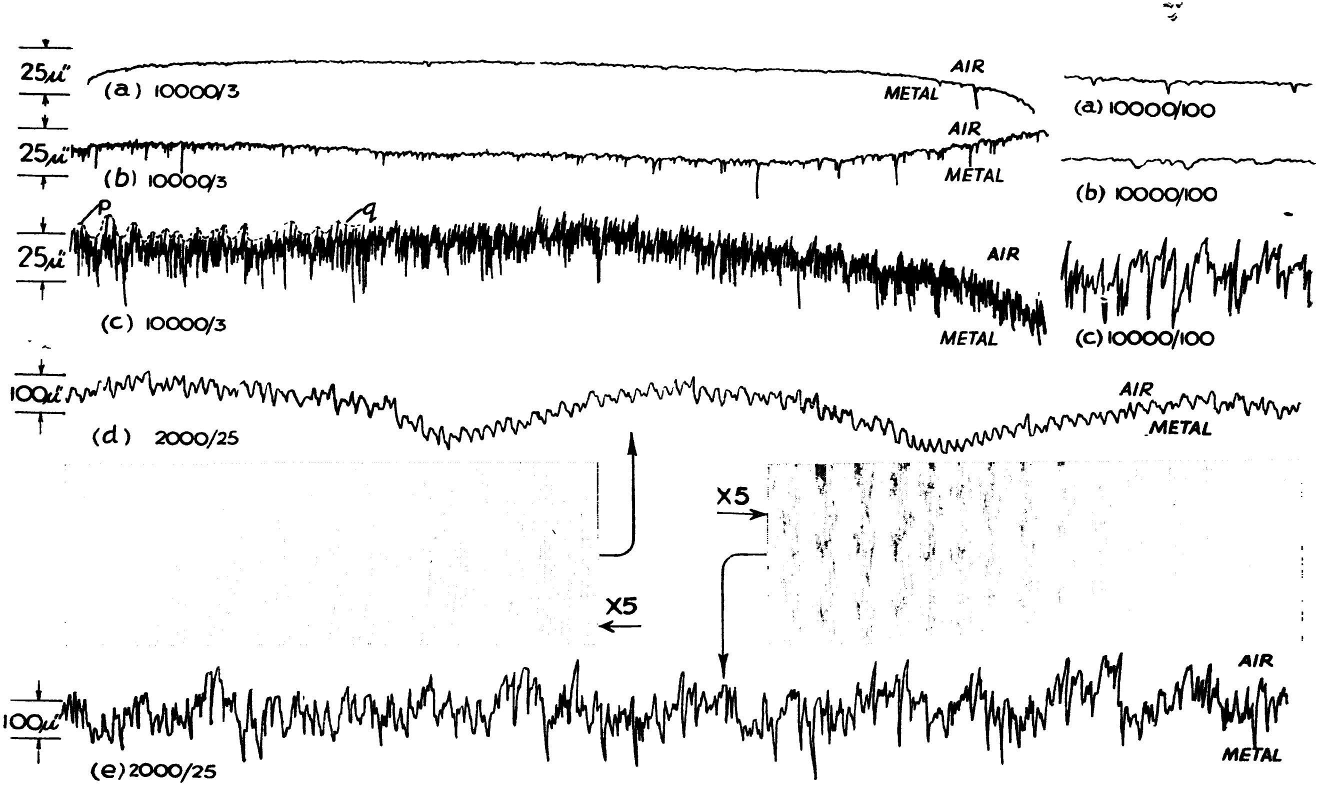


Fig. 17.2: Graphs of real surfaces showing different errors in combination

possible defects, before being able to decide whether or not the profile shows Secondary Texture. Generally, but not always, the Secondary Texture has a much greater crest spacing than the Primary Texture. In appearance it can be very deceptive, the height of the most obvious chatter marks on ground surfaces being sometimes much less than that of the scratch marks.

Some examples showing what different combinations of texture can look like are given in Fig. 17.2. The first three (*a*, *b*, *c*) show the profiles of cylindrical steel specimens about 1 in. in diameter, finished respectively by lapping, superfinishing, and grinding (average toolroom grade). A 0·0001 in. stylus was used throughout. The graphs at 3 × horizontal magnification cover the whole length of the specimen while those at 100 × cover a short length only to show the nature of the scratch marks. The first two specimens show normal scratch texture combined with an error in shape: as might be expected there are no significant undulations of greater spacing than that of the scratch marks. In the third example there is just a suggestion of secondary texture (i.e. the envelope *p q* of the crests of the scratch marks) but its height is small compared with that of the scratches. The last two examples, supported by photomicrographs, show how deceptive appearances can be. In one case (face turning with a loose cross-slide) there is an undulation which has many times the height of the scratch marks, although it was hardly detectable by eye, while in the other (straight flat grinding) what might be taken for a system of immense chatter marks is found to be almost innocuous, the height of these marks being less than that of the normal scratch marks. The illusion of deep chatter marks is here caused by a periodic change in the direction of the scratch marks without any corresponding change in their general level, this phenomenon being quite common. Mr. W. E. R. Clay (Rolls Royce Co.) has found that in normal grinding widely spaced undulations having a height rather less than that of the scratch marks are usual. Cases like example *d* indicate some gross fault in the process and are rare.

Both in research and in the workshop, surfaces need to be considered in as broad a way as possible, for no one method of examination, and especially no one numerical assessment, can be expected to tell the whole story.

Topographic Assessment of Texture. Plan View—The Microscope. A full account of the principles of the optical microscope will be found in the references (1 and 5) and a few somewhat random notes must here suffice. The microscope is used for examining the plan view, and magnifications from unity (that is naked-eye observation) up to the highest of which the microscope is capable are needed according to the crest spacing of the texture under observation.

A good metallurgical microscope is an asset for any kind of laboratory investigation, and a simple form may well find a place in an inspection department; but it will not take long to discover that the true interpretation of what is seen is often perplexing, particularly in the case of surfaces finished by abrasive processes.

The conditions of illumination can greatly affect the appearance of the image, as can small changes of focus.

When examining very fine surfaces, the crest spacing of which may be no more than a few hundred-thousandths of an inch, the resolving power of the objective, which is limited by the finite magnitude of the wavelength of light, becomes important. For the most perfect equipment and conditions, the closest scratch spacing which can be resolved is given by the formula $0{\cdot}6\lambda/\text{N.A.}$, where λ is the wavelength of the light used (0·00002 in. for green light) and N.A. = the Numerical Aperture of the microscope objective (from 0·1 for low powers up to 1·4 for high powers). Magnification in excess of what will make texture on the limit of resolution just visible is likely to reduce rather than increase the clarity of the picture.

Another peculiarity worthy of note is that the microscope can be very selective in what it reveals, and tends to put greatest emphaiss on whatever texture has flanks of greatest inclination to the surface. An example of this is given in Fig. 17.3. Using the same machine and wheel throughout, the specimens were ground to different degrees of roughness (shown by the profile graphs) by changing the mode of dressing and using the wheel. The range of texture thus produced is considerable, the roughest specimen having a height of about thirty times that of the smoothest. While successive specimens could be told apart by sight and touch, there is hardly anything to choose between the photomicrographs, which reveal nothing but the most closely spaced scratch marks.

Detail too fine to be resolved by the optical microscope (for example the rupture marks on very fine surfaces) has been revealed by the electron microscope, with the aid of which it has even been possible to find residual scratch marks in the Bielby layer formed on optically polished glass (Fig. 17.4). It is perhaps interesting to recall that while the early opticians conceived polishing as the formation on the surface of scratches too fine to affect the reflection of light, Bielby

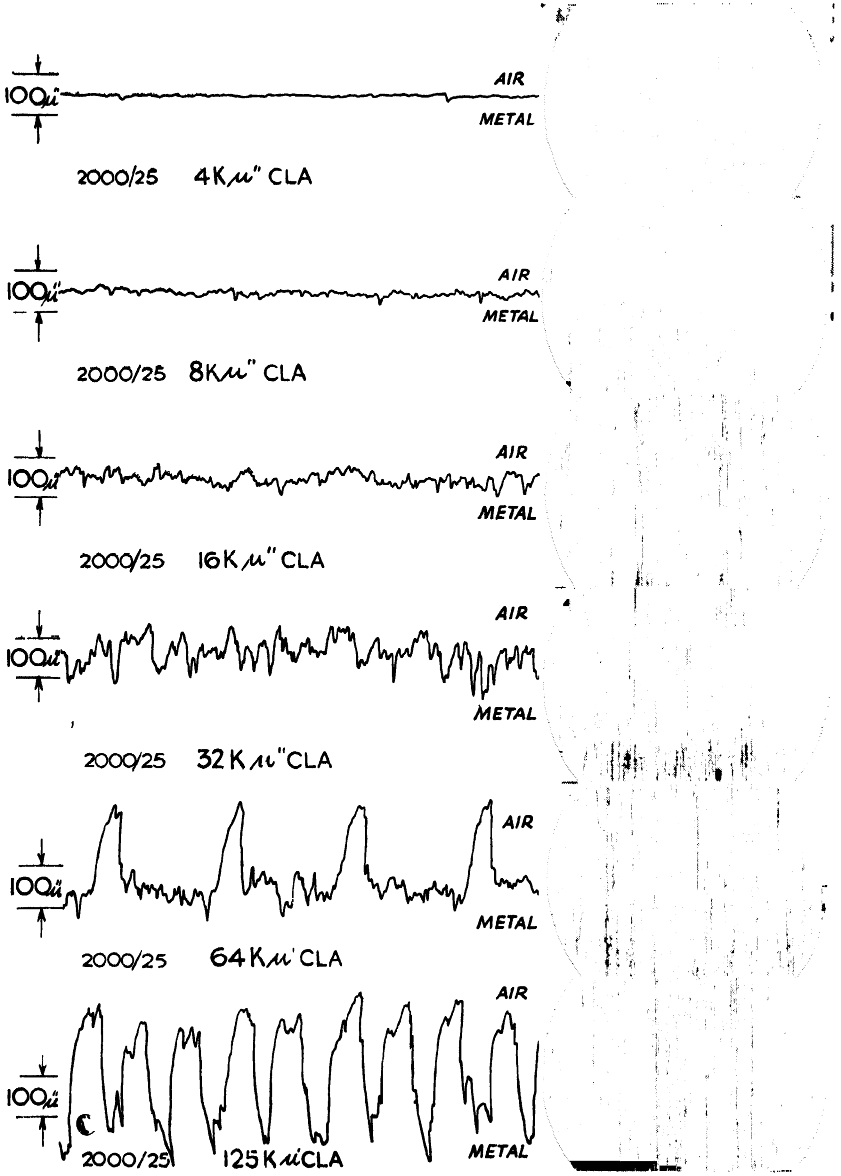


Fig. 17.3. By putting undue emphasis on the most closely spaced scratch marks, the microscope causes the surfaces shown above to look much alike

(Ref. 23) conceived polishing as the formation of a non-crystalline (amorphous) layer formed by molecular flow. Now the electron diffraction camera has substantiated Bielby's theory, while the electron microscope has shown that the earlier views had substance too. Even the electron microscope, however, has limitations, and molecular details have still to be seen.

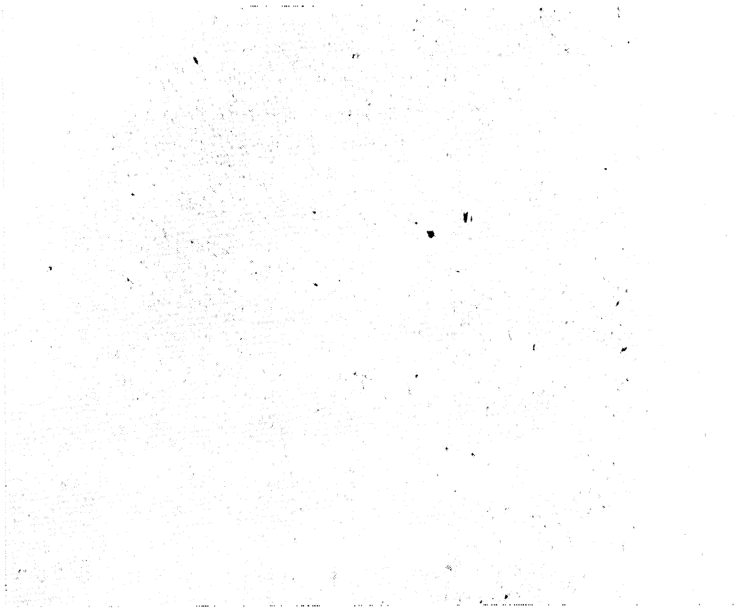
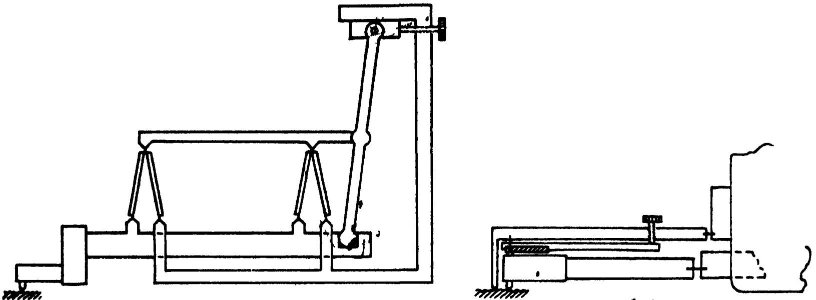


Fig. 17.4. Electron micrograph of well polished glass surface, showing residual scratches not detectable by optical or stylus methods. X2,000 in direction of shadow of dust particle. X350 transversely

CROSS-SECTIONS NORMAL TO THE SURFACE—STYLUS INSTRUMENTS. If a sharply pointed stylus, resting lightly on the surface, is traversed slowly across it, and the up and down movements of the stylus relative to a suitable datum are magnified and recorded on a base representing the distance traversed, a graph representing the cross-section will be obtained.

The Stylus is generally a pyramidal or conical diamond with a flat or rounded tip. The American Standard calls for a 60° cone with a radius of 0·0005 in. (in special cases 0·0001 in.) at the tip. In this country a 90° pyramidal form, with a flat or rounded tip not more than 0·0001 in. in width or radius is generally preferred; but comparator instruments with tips of 0·0005 in. and 0·001 in. radius have been introduced, and tips down to 0·00003 in. wide have been used for research.

When a rounded tip is used the limiting condition for full penetration into the scratches is that the radius of curvature of the bottom of the scratch should be greater than that of the stylus. No matter how narrow the scratch, therefore, there must always be a chance that it will also be shallow enough for the rounded stylus to reach to the bottom, and there is no definite scratch width below which the rounded stylus must cease to function. With a flat-tipped stylus, on the other hand, the limiting condition is simply that the scratch should be wider than the flat (with a small allowance for the sloping sides) and is substantially independent of the depth. This compares with the optical resolving power of the microscope, where the minimum observable scratch width is again independent of the depth.


(a) Model 2 – *Talysurf*

(b) Model 3 – *Talysurf attachment*

Fig. 17.5. Straight-line datum devices used in Talysurf instruments

A useful guide to the maximum permissible load on the stylus is given by a formula in the American Standard B–46/1955, Max. Force in grammes $= 0{\cdot}00001 \cdot \times$ (Tip radius in micro-inches)^2.

The Datum should conform with the nominal shape of the surface to be tested, and unknown departures from this shape over the required length should be small compared with the smallest height to be measured. This requirement becomes progressively harder to meet as the nominal shape becomes more complex and as the irregularities become smaller in height and greater in spacing. For surfaces that are nominally straight in the direction of measurement, a well finished lubricated slideway will provide a datum suitable for the rougher surfaces; but for the finer surfaces, for which the local errors should not exceed one or two millionths of an inch, the uncertain thickness of an oil film can be troublesome. In the Model 2 Talysurf instrument, straightline linkages having elastic ligaments for their hinges were used, as shown in Fig. 17.5*a*. Local errors were less than 2 μin. and general straightness was within 7 μin. over the traverse of ¼ in. A simpler though more limited arrangement used with the Model 3 Talysurf instrument is shown in Fig. 17.5*b*. Here a rounded foot mounted on the pick-up body immediately above the stylus rides along an easily renewable optical flat which is positioned over the surface to be tested.

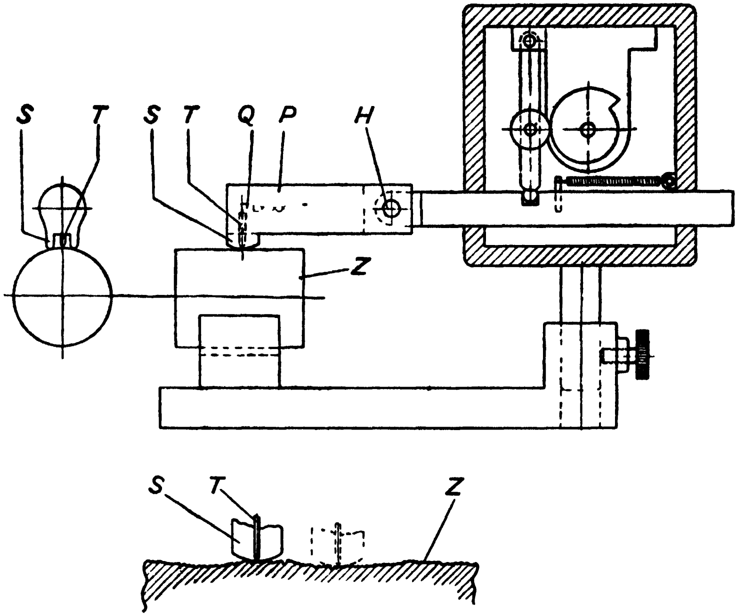


Fig. 17.6. Stylus instrument in which the datum is generated by a rounded skid S sliding across the surface

The slideway or linkage, apart from mechanical errors, permits a true cross-section of all undulations to be obtained regardless of their spacing; but the need for accurate levelling and great rigidity of the framework has led to the widespread use of approximate devices involving a member sliding on the surface to be tested. In one form shown diagrammatically in Fig. 17.6 (which will be mainly self-explanatory) the pick-up body *P* is hinged to the driving mechanism at *H*, and provided with a pair of rounded feet *S* adjacent to the stylus *T*, at least one of the feet resting on the specimen *Z* and sliding across it together with the stylus. *Q* represents a displacement-sensitive device. A single rounded foot may be used, as shown in Fig. 17.7*a*, or a swivelling pad which fits the nominal shape of the surface at least in the direction of motion, as shown in Fig. 17.7*b*. For distinction, the rounded foot will be called a "skid" and the swivelling pad a "shoe". The quantity revealed by the instrument is the vertical movement of the stylus relative to the skid or shoe.

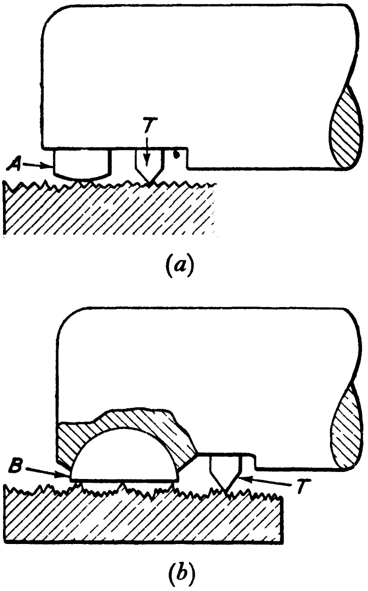


Fig. 17.7. Rounded skid A, and swivelling shoe B. T is the stylus

In the case of the skid, the datum is the locus of the centre of curvature of the skid as it slides over the surface. When the principal crests are close enough together, the locus may approximate closely to its true form as shown in Fig. 17.8*a*; but as the spacing increases so will the movement of the skid, until finally it moves up and down as much as the stylus, as in Fig. 17.8*b* and 17.8*c*. Since the skid and stylus cannot touch the surface at the same point, the result will depend on the relative phase of the two movements as well as on their amplitudes. Phase effects will be found no matter where the

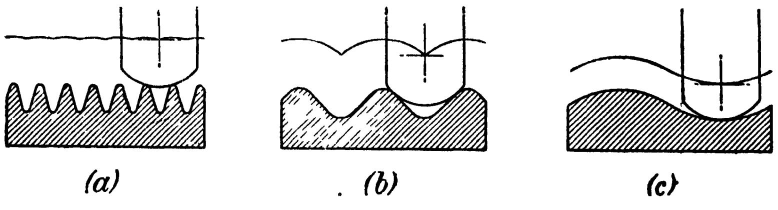


Fig. 17.8. The rounded skid provides a serviceable datum only for those components of the texture whose crests are close enough together

skid is positioned relative to the stylus—whether in line with it or at the side (Ref. 2). At one end of the range the skid and stylus will move up and down together and the relative movement can fall to zero, while at the other end their movement will be 180° out of phase and the height of the resulting graph can rise to twice its proper value. For an intermediate phase the graph may still be nearly correct even though the skid is moving up and down as much as the stylus. When, as so often happens, the spacing is irregular, some undulations may be exaggerated and other undulations diminished in such a way that although the graph is in a sense false it still gives the right impression of the surface. The practical limits of the skid are therefore not calculable and have to be learned from experience. The bulk of modern instruments use skids from ¼ in. to 2 in. radius, and are serviceable for most of the finer cut and abraded surfaces, for which the characteristic spacing is generally less than 0·03 in. Unfortunately such instruments are also used all

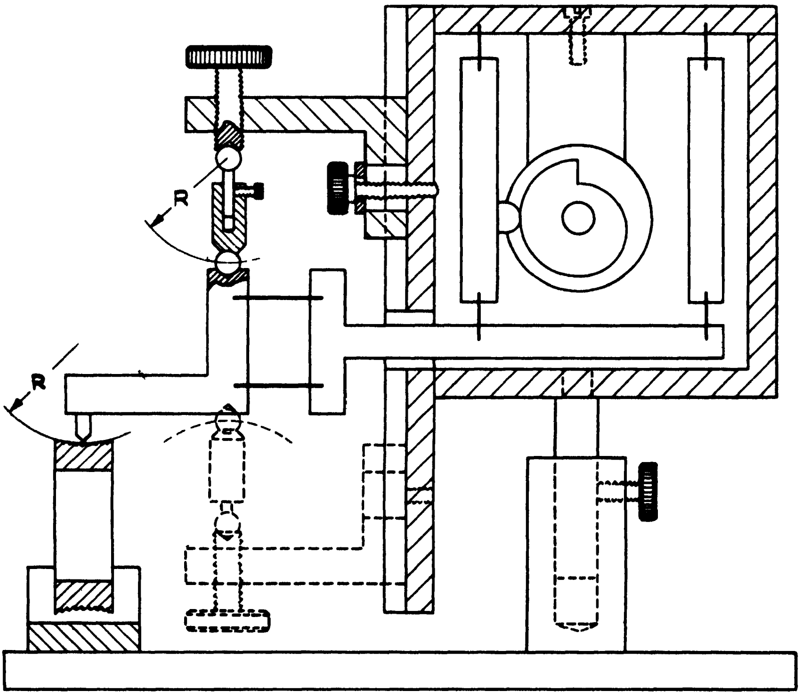


Fig. 17.9. Principle of arcuate guiding used in Talysurf instruments

too often for measuring the rougher surfaces produced by milling, scraping, and planing, or those afflicted with widely spaced chatter marks, for which surfaces the resulting representation may be very misleading.

The difficulties resulting from the curvature of the skid can often be largely avoided by means of the shoe. Provided the crests are reasonably uniform in level, and are spaced apart by not more than half the length of the shoe, a very serviceable datum will be provided. The shoe tends to be more costly and bulky than the skid, and to need more careful alignment in holes. The properties of skids and shoes are discussed in Ref. 2.

Curved surfaces can often be tracked by approximating to them the arc of a circle which in the case of the Talysurf instrument has been generated with sufficient accuracy by a pivoted link of appropriate length as shown in Fig. 17.9.

When the requirement is to measure a surface of revolution in the circumferential direction, it is often necessary to measure right round the part in order to reveal the chatter marks and lobes which in this direction are generally of principal importance.

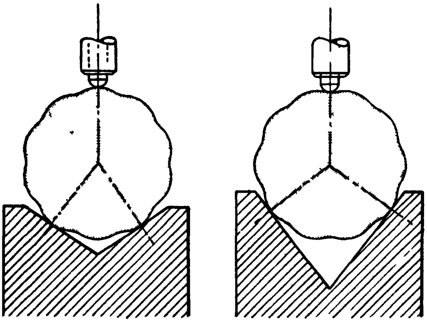


Fig. 17.10. Assessment of roundness in a V-block. Crests engaging V's and indicator (*a*) in phase, (*b*) out of phase

One practical method of measuring right round derives from the well-known test of rotating the piece in a V-block under an indicator. It is essential, however, that the angle of the V should be adjusted according to the number of crests round the circumference. The best condition is that crests should simultaneously engage the V's and the stylus as shown in Fig. 17.10*a*: this gives an indication approximately twice the radial height from peak to valley, because the rise and fall of the part in the V-block will be in phase with that of each undulation as it passes under the stylus. If the angle is such that crests engage the V when a valley engages the stylus, as shown in Fig. 17.10*b*, the movements will be in opposite phase and may cancel out completely. An example of this is shown in Fig. 17.11, which includes a polar graph of the same part.

When the lobes or chatter marks are uniform, as in Fig. 17.11, the V-block method gives dimensionally accurate results, but when they are irregular, as often happens with ground specimens, the resulting graph can only be taken as a rough indication of the order of out-of-roundness.

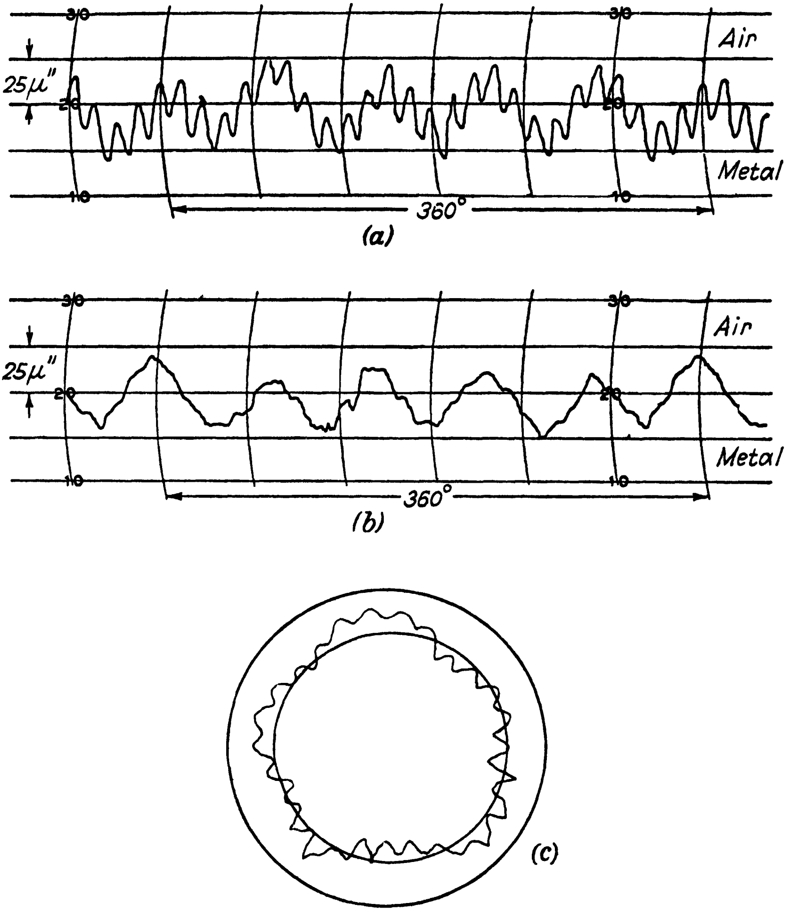


Fig. 17.11. Graph (*a*) shows roundness of gudgeon pin having 26 irregularities superimposed on 5 lobes of approximately the same height, properly measured in a V-block of angle to give in-phase condition for both sets of irregularities. Graph (*b*), of the same specimen, shows how undulations can be missed if an incorrect V-angle giving out-of-phase condition happens to be used. Graph (*c*) is a polar graph of the specimen

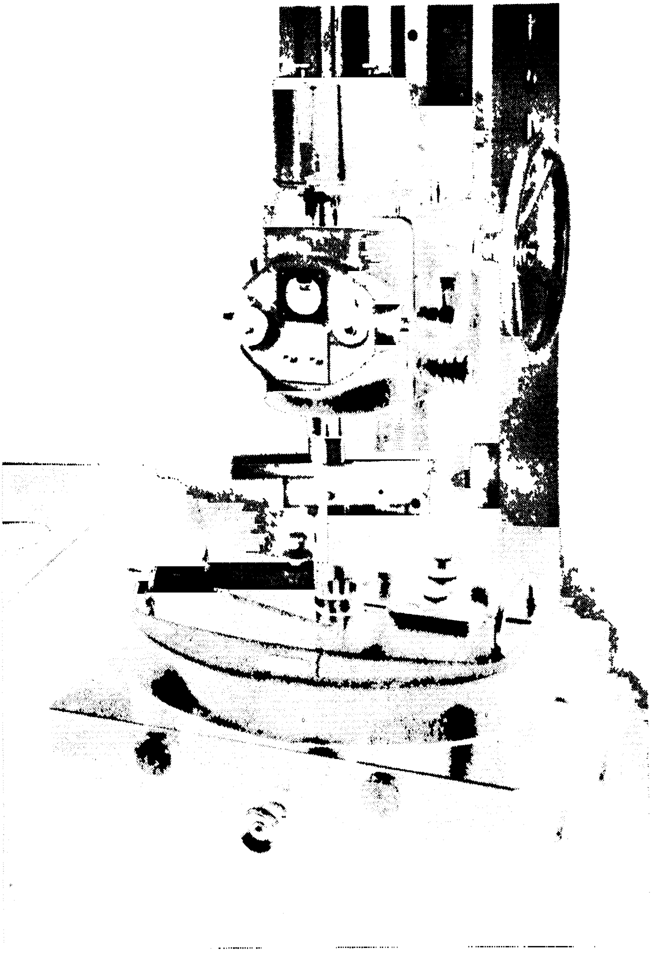


Fig. 17.12. Spindle head and work-table of Talyrond instrument, showing stylus arm engaging taper roller race

In another method exemplified by the Talyrond instrument illustrated in Fig. 17.12, the datum is provided by the axis of rotation of a precision spindle. Variations in the radius of a part resting on the work-table are detected by the stylus of an electric displacement indicator which is carried on the spindle and rotated round the part. The variations are recorded on a polar chart. When looking at the resulting graphs, of which some examples are shown in Fig. 17.13, it must be realized that they are representations not of the shape of the part but of the departures from the true shape, plotted on a radial scale of magnification which is vastly greater than the circumferential

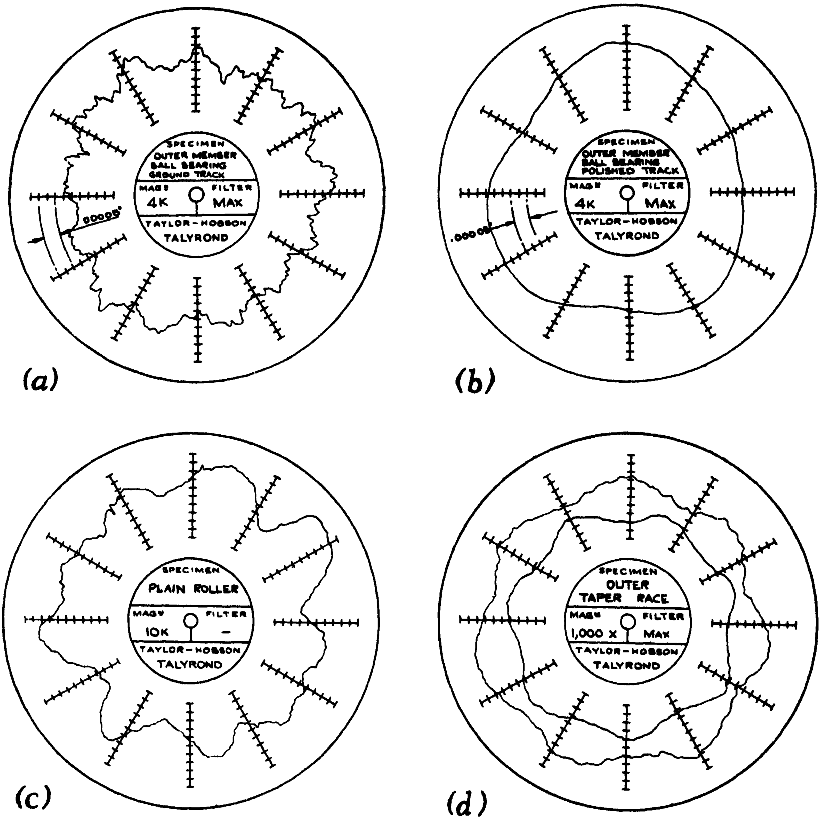


Fig. 17.13. Polar graphs showing deviations from roundness. Diametrally opposite points on the specimen are diametrally opposite through the centre of the chart paper. Specimens (*b*), (*c*), and (*d*) thus have very nearly constant diameter. Graphs for (*d*) show inside and outside of race

scale at unit angular magnification. The resulting distortion, analogous to that of surface finish profiles but generally even more violent, often leads to convex portions of the actual surface being represented by concave portions of the graph, so that thought and arithmetic are needed before the true *shape* can be deduced. An example is shown diagrammatically in Fig. 17.14, where the departures of an original part drawn solid from a true circle drawn dotted are scaled up 2, 4, and 8 times on a base circle of constant diameter.

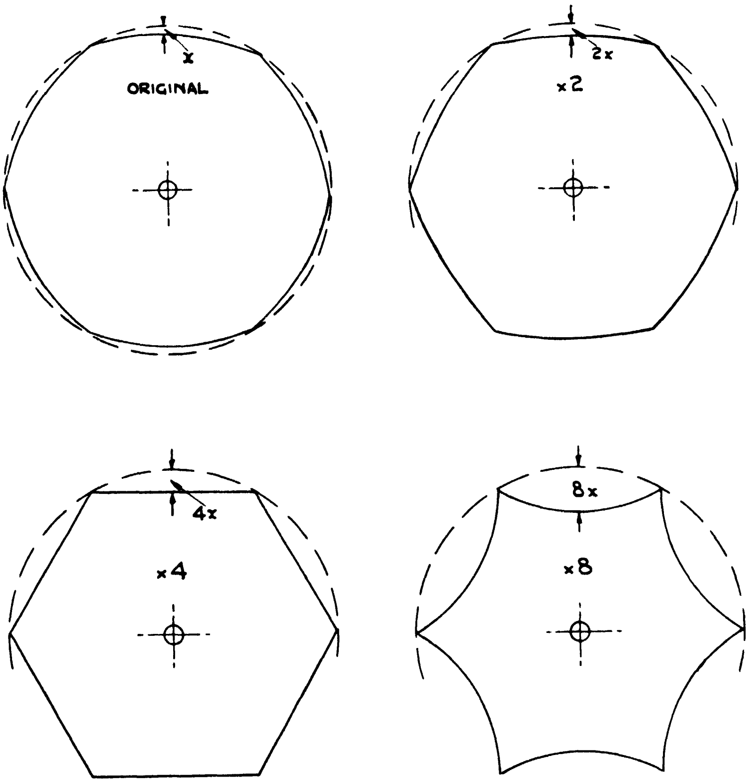


Fig. 17.14. Figures showing how progressive scaling up of departures from perfect roundness without corresponding increase in size of base circle leads to distortion of shape

The limiting accuracy is set by that of the spindle, which in the Talyrond instrument has a spherical bearing at the lower end to provide both axial and radial constraint, and a slow taper running in a self-aligning bush at the upper end. Full hydrodynamic lubrication with oil films a few millionths of an inch thick is maintained at the recording speed of 3 r.p.m., and the usual order of accuracy is that the locus of a point off the axis of the spindle will not deviate from a true circle by more than 1 to 2 μin.

A discussion of some of the problems of specifying errors in roundness, both of the part and of the instrument, will be found in Ref. 47.

MAGNIFYING DEVICES. For all the finer surfaces, the need is for very high magnifications with very light operating forces.

A lever magnifying up to 160X on smoked glass (the record being subsequently magnified 100X more) is used in the Tomlinson skid instrument.

In the David Brown "Topograph" a pneumatic recorder was used, the recorder being controlled by the pressure variations in a jet of air which, emerging from one small nozzle and entering another, was partially intercepted by a blade moved by the stylus.

In many ways electrical methods have been found the most practical. They lend themselves to the production not only of a profile graph but also of a numerical assessment of the surface. Devices for converting mechanical displacements into electric currents (often called pick-ups or transducers in such a context as the present one) are of two basic kinds:

1. Carrier modulating devices, in which the magnitude of a current (the carrier) is controlled (modulated) at every instant of time according to the position of the stylus relative to the datum, regardless of how long the stylus remains in a given position.*
2. Current or Potential generating devices, in which a current or potential is generated according to the *motion* of the stylus as it is displaced from one level to another.†

Modulated Carrier Instruments. The electrical principle of a carrier modulating instrument (the Talysurf) is shown diagrammatically in Fig. 17.15*a*. A pile of E-shaped stampings with a winding round each of the outer limbs is mounted within the body of the pick-up. An armature *M* carrying a stylus *T* is pivoted over the central limb so as to leave small air gaps between the armature and each limb. The outer limbs, sharing the central one, then form two differential air-gapped inductances whose impedances depend on the length of the air gaps. An alternating current of high frequency (the carrier) flows through each of the coils, its magnitude depending on the impedance of the coil. Thus the position of the stylus controls, or in electrical terminology "modulates", the carrier. It is possible

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* Some commercial examples are the Talysurf Models 2 and 3, the Proficorder and the Perthometer. The first instrument of this kind to be put on the market, the Talysurf made by Taylor Taylor and Hobson, appeared in 1940.

† Some commercial examples are the Profilometer, Surfagage, Microtest, Talysurf Model 100. The first instrument of this kind to be put on the market, the Profilometer designed by the late Dr. E. Abbott, appeared in 1936, and derivatives of it continue to be sold by the Micrometrical Corporation.

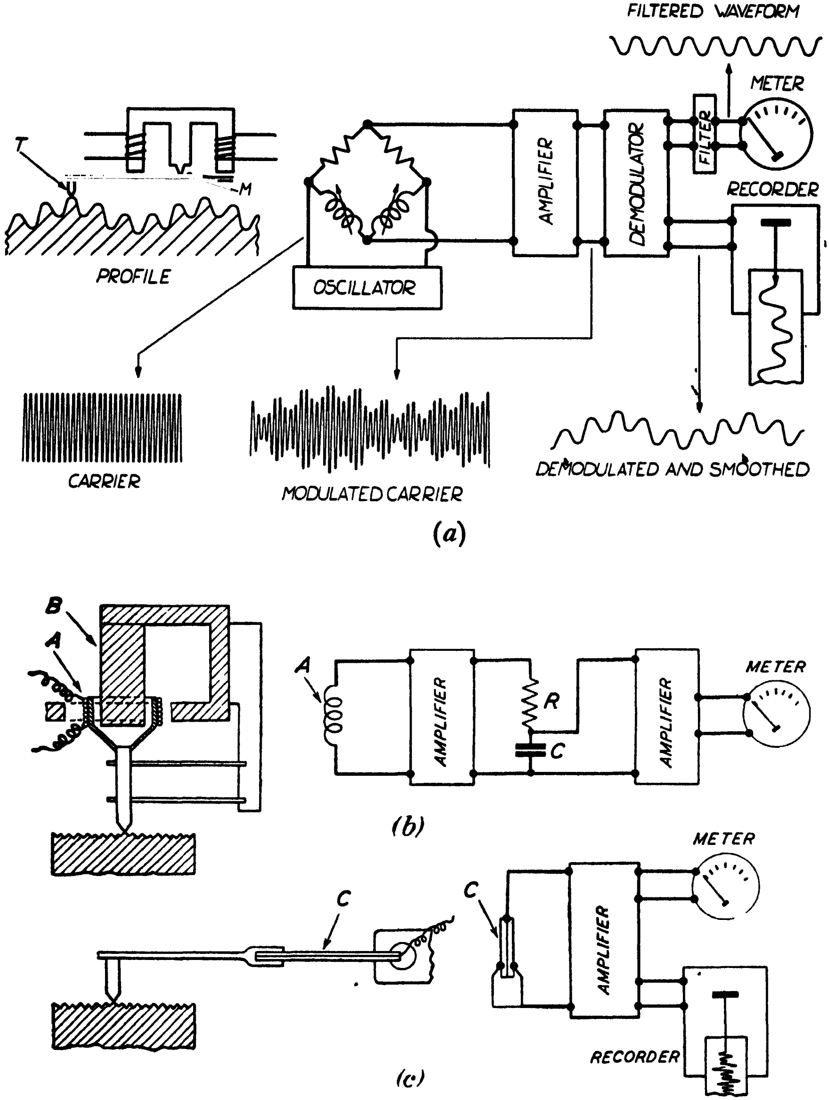

Fig. 17.15. Electrical principle, (*a*) of carrier modulating instrument, (*b*) of current generating instrument, (*c*) of potential generating instrument

to connect the coils, for example, in the way shown in the diagram, so that only the changes in the current, which are proportional to the changes in the air gaps, are passed on to the amplifier. It is also possible to vary only one of the inductive arms of the bridge, the other being fixed, and to linearize the output by resistive loading this has been done in the Model 3 Talysurf shown in Fig. 17.16

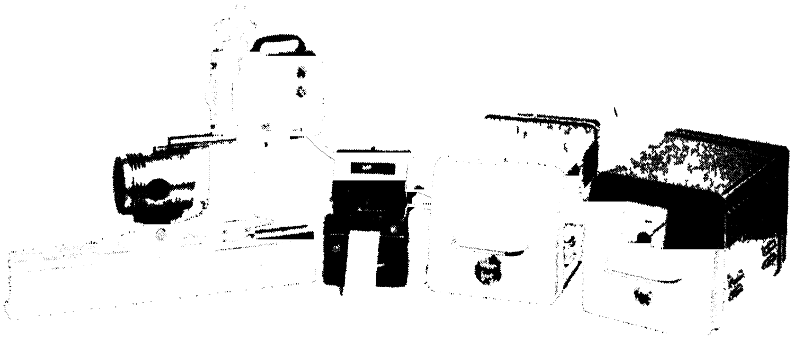

Fig. 17.16. Model 3 Talysurf instrument

After amplification, the carrier frequency is separated from the modulating frequencies, and suppressed in such a way as to leave only a current varying according to the successive displacements of the stylus. This part of the process is known as de-modulation. The resulting current can be further amplified and used to control a recorder or actuate an integrating meter. In the latter case a wave-filter is inserted to suppress the very low frequencies and confine the measurement to the higher frequencies representing the texture: this will be discussed further on. A good account of the principles of carrier modulation and de-modulation will be found in Ref. 3.

Carrier modulating instruments are ideal for obtaining profile graphs, because they can faithfully reproduce every movement of the stylus relative to the datum regardless of the spacing of the crests i.e. of the frequency at which the stylus rises and falls.

Generating Instruments. A moving-coil type of generating instrument (the Profilometer illustrated in Fig. 17.17) is shown diagramatically in Fig. 17.15*b*. A small coil A mounted on the stylus shaft is moved through a radial magnetic field provided by the magnet *B*. The current generated by the motion of such a coil is proportional to the amplitude and to the frequency of vibration, the frequency in the present context depending on the spacing of the irregularities and the speed of traverse across the surface. The output from the amplifier which is used to operate the indicating instrument *M* must, however, be independent of frequency over the working range. In the Profilometer a simple correcting circuit, *R*, *C*, inversely proportional to frequency, is therefore inserted between two sections of the amplifier. In the range of frequencies for which the reactance of the condenser *C* is small compared with the resistance *R*, the fraction of the output potential tapped off to feed the second section of the amplifier will decrease linearly with frequency and exactly compensate for the rise in the pick-up. When the reactance becomes comparable with that of the resistance the corrective action ceases, this determining the low-frequency limit of the instrument. The Profilometer is generally used for numerical assessment only. It can be traversed across the surface manually, but is best used in conjunction with a constant-speed motorized driving unit.

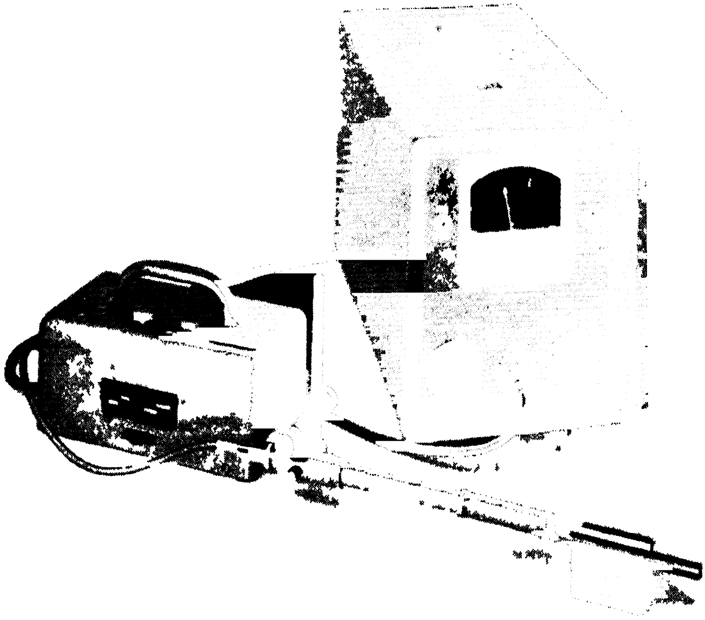

Fig. 17.17. Model QA Profilometer

An elementary form of potential generating pick-up using a piezo-electric element *C*, generally made of Rochelle Salt, Barium Titanate or Lead Zirconate is shown diagrammatically in Fig. 17.15*c*. Flexure of the element produces a voltage proportional to the strain. In practice, because of leakage effects, the piezo device responds to the motion rather than to the position of the stylus.

Piezo-electric devices set the problem that while the output for a given amount of flexure increases with the stiffness of the element, high stiffness is incompatible with low stylus forces. This has led to pick-up designs in which the initial movement necessary to bring the stylus into contact with the surface is not accompanied by flexure of the piezo element. In these designs the stiffness associated with the initial movement is kept to a low level, and the relatively high stiffness of the piezo element is made operative only through the relatively small displacements resulting from the surface irregularities. In this way a reasonable compromise between stylus force and electrical output can be secured.

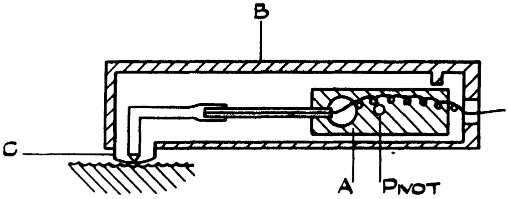

Fig. 17.18. Principle of Sigma Microtest

In the example offered by the Sigma Microtest (Fig. 17.18), a piezo-electric cartridge, *A*, is pivoted within an outer casing *B* having skids *C* which slide over the surface, and the stylus is held in contact with the surface by gravity or by a spring of low stiffness. The effective "datum" is provided by the inertia of the cartridge. In taking up the initial position, and at low frequencies, the cartridge and stylus rotate together freely about the pivot, and there is a little flexure of the piezo element, but at high frequencies the inertia is sufficient to oppose rotation and the stylus alone is displaced, bending the relatively stiff element according to the surface irregularities. The skids act mainly as a steady, and because of the pivoted mounting of the cartridge the instrument is comparatively insensitive to the effects of hand wobble.

In the Model 100 Talysurf (Fig. 17.19), the pick-up body *A* is hinged to a motorized driving arm *B* and biased to bring the skid *C* into contact with the specimen by a spring *D*. In its free position the skid stands a little above the level of the work-table. The stylus arm *E* and the piezo element *F* are mounted on a cross bar *H* resting on a knife edge *J*, and are biased by a spring *K* which keeps the stylus in contact with the specimen. In its free-position the stylus stands a little above the level of the skid under a force of about 0·2 grammes which is reasonably constant through the working range of a few thousandths of an inch. After the workpiece has depressed the skid and stylus to their operative levels in contact with it, and after the motor has been started, the rear end of the piezo element is automatically clamped by the pincer-like arms *L* which, pivoted to the ends of the electro-magnet cores *M*, are drawn in to grip the iron tip *N* through which the flux passes. Surface irregularities extending below the starting level of the stylus depress it directly thus bending the element, while for those extending upwards the stylus follows under the action of the force in the spring *K* until the force becomes zero, thus bending the element in the opposite direction. It is sufficient if the spring force becomes zero when the stylus is just above the level of the highest peak likely to be encountered. Thus the crystal has to be bent only enough to follow the profile and the initial movement to bring the stylus from its free position into contact with the surface is not included. In practice the stiffness of the element may be five or ten times greater than that of the biasing spring. The

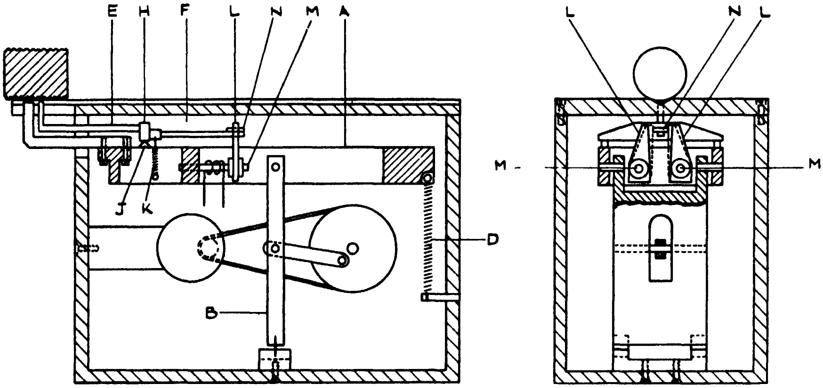

Fig. 17.19. Principle of Model 100 Talysurf instrument

complete instrument (Fig. 17.20) has the feature that the skid and stylus engage the underside of the work which rests on the table, thus facilitating rapid operation.

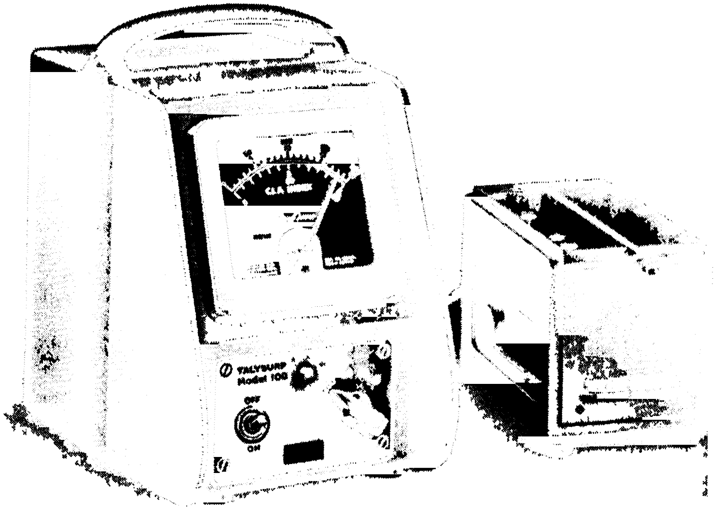

Fig. 17.20. Illustration of Model 100 Talysurf instrument

Yet another solution to the problem of the "stiff" transducer is found in the General Motors "Surfagage". Here the transducer has the form of a thermionic valve (the RCA 5734) of which one electrode (in this case the anode) is carried on a rod passing through a flexible diaphragm sealed to the end of the envelope, so that its distance from the other electrodes can be controlled from without. Changes in separation produce proportional changes in the current through the valve. The stiffness, however, limits the available range of movement to little more than the peak-to-valley height of the roughest surfaces to be measured. In the "Surfagage" (Fig. 17.21) the stylus shaft *A* is flexibly mounted on leaf springs *BB* to provide the large range of initial movement necessary for a manually controlled instrument, and actuates the control rod *C* of the valve through a viscous coupling formed by a U-shaped member *D* mounted on the rod and surrounding though not touching the shaft, the space between the two being packed with a silicone grease. At low frequencies the U slips past the shaft; but at the high frequencies produced by the surface irregularities the grease acts as a rigid coupling which transmits these movements of the stylus to the anode. A form of viscous coupling is used also in the Brüel and Kjaer surface meter.

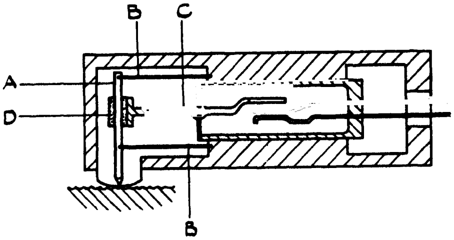

Fig. 21. Principle of Brush Surfagage

Transmission Characteristics and Wavelength Cut-off. Although it is convenient to consider the performance of instruments in terms of the wave-lengths or crest spacings by which the surfaces to be examined are typified, the behaviour of electrical circuits is determined fundamentally by the frequency of the signals passing through them. Thus wave-length and frequency have to be related, and this is accomplished by controlling the speed of traverse, the frequency f that results from a wave-length λ at a speed of traverse s being given by the simple relation $f = s/\lambda$.

Consider now a number of surfaces each having irregularities in the form of equally spaced sine waves, the height on all the specimens being the same but each specimen having a different wavelength, as shown in Fig. 17.22. Imagine that the instrument, assumed to have a datum of adequate quality, is traversed at constant speed across each surface in turn, and that the indications (amplitude of pen or reading of meter) are plotted against the wave-length. For the recorder of a modulated carrier instrument the result shown by the solid curve may be expected. For very short wave-lengths there will be no response because the stylus is not able to enter the grooves. As the spacing increases the indication will rise, but once it has become sufficient for the stylus to reach to the bottom, there will be no further increase however great the spacing becomes.

Since the output of electrical instruments of the generating kind is dependent on the *motion* of the stylus, the output tends naturally to fall off below a certain frequency, that is above a certain wave-length, for example as shown dotted, even though the stylus continues to rise and fall over the irregularities. Only within the range of wave-lengths for which the curve is level will the indication be a measure solely of the amplitude and be independent of wave-length. Although unsuitable for graphing instruments required to show the true shape of the profile, this type of characteristic is required for averaging instruments as a means of picking out for measurement specific groups of irregularities. In the case of carrier modulating instruments, the required characteristic is obtained for purposes of integration by means of a wave-filter in the path of the current actuating the averaging meter.

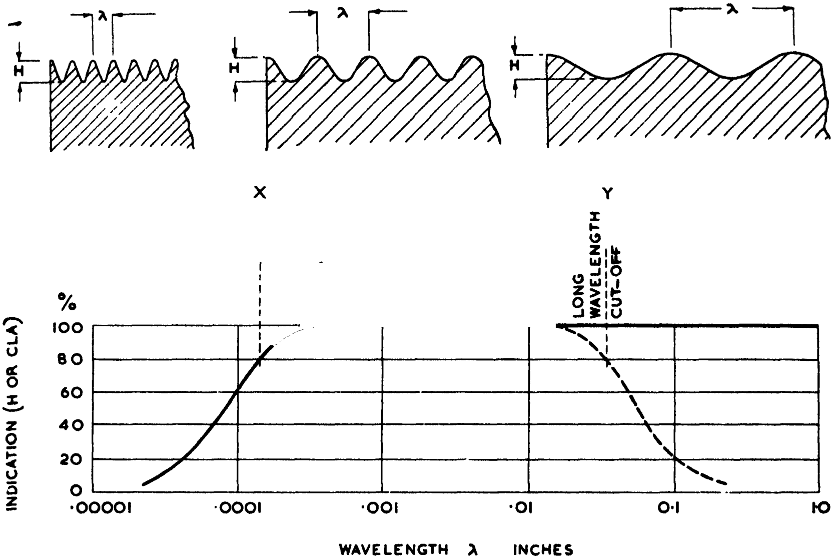

Fig. 17.22. Operative effect (transmission characteristic) of electric wave-filter

The transition from the operative to the inoperative region not being abrupt, it is usual to assess the short wave-length cut-off *X* and the long wave-length cut-off *Y* at some agreed fraction of the maximum transmission. In B.S. 1134 : 50 the suggested fraction is 80 per cent while in B. 46 : 55 it is 70 per cent; fortunately this disparity is of little consequence. The range between *X* and *Y* is called the pass band. Although the rate of attenuation did not seem critical (Ref. 2) it is desirable that it should be standardized. The rate accepted in both British and American Standards is one for which the maximum slope represents a four-fold change in amplitude for a two-fold change in wave-length; in the language of electrical power this is described as a rate of 12 decibels per octave.

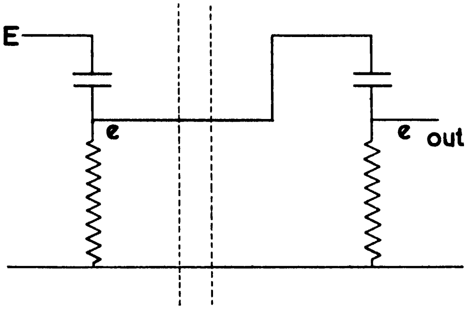

Fig. 17.23. Simple RC filter circuit

Nature and Position of Filter. The rate of attenuation accepted in the British and American Standards can be provided by two resistance-capacitance networks of equal time constant* connected in cascade as shown in Fig. 17.23. Generally the networks are separated by a buffer (for example a valve) represented by the dotted lines, but they can be directly connected provided the impedance of the second is several times greater than that of the first. The principle of operation cannot be fully explained without reference to an introductory discussion of the principles of alternating current circuits, for example as given in Ref. 3. Briefly, and with many gaps in the argument, the capacitor and resistor receiving a signal of voltage E act as a frequency-sensitive potential divider. The behaviour of the resistor is independent of frequency but that of the capacitor is not, its opposition to the flow of alternating current (its *reactance*) decreasing with increasing frequency. At high frequencies for which the reactance is small compared with the resistance R, the fraction of the input voltage tapped off, that is $\frac{e}{E}$, is substantially unity; but at low frequencies for which the reactance becomes progressively greater than R the fraction falls off, and is also displaced in phase (Ref. 2). When two circuits of equal time constant are used, the final output e_{out} will be equal to $\left(\frac{e}{E}\right)^2$.

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* Time constant = resistance in ohms × capacitance in farads.

The reactance of a capacitor of capacitance C farads at a frequency of f cycles per second is

$$\frac{1}{2\pi fC}\ \text{ohms},$$

and if R is the resistance also in ohms,

$$\frac{e}{E} = \frac{R}{\sqrt{\left\{R^2 + \left(\frac{1}{2\pi fC}\right)^2\right\}}}$$

while the accompanying phase shift is

$$\frac{1}{2\pi fCR}$$

The form of the denominator is due to the fact that the voltage produced across the condenser is 90° out of phase with that across the resistor. This accounts for the shape of the transmission characteristic—a long flat portion followed by a relatively quick transition to the region of attenuation.

The combination of attenuation and phase shift may cause some distortion of wave-forms having significant frequencies coming just around the cut-off. The effect on the appearance is generally much greater than that on the average reading which is often but little affected (Ref. 2).

Although it is convenient to speak and think of the wave-filter as though it were an entity, the required attentuation is often secured by suitable proportioning of components already needed for other purposes. For example in a carrier modulating instrument the two RC networks can form two of the valve couplings in the low frequency amplifier feeding the average meter. In the case of piezo-electric pick-ups, one of the networks can result from the self-capacitance of the crystal and the load into which it works (though this arrangement may be sensitive to temperature and to leakage resulting from humidity). In the case of the moving coil pick-up the proportions of the RC frequency-correcting circuit can be chosen to have the required effect. In some instruments only a single network is used; the rate of attenuation may then be rather gradual.

Calibration of Instruments. In the case of an instrument having a recorder responsive to sustained displacement of the stylus and also an average meter, a fundamental approach is to calibrate the recorder from two gauge blocks having an accurately known difference of thickness, then to take a profile graph of a reasonably uniform specimen having irregularities coming well within the pass band, to determine the average value graphically by a standardized procedure for example as given in B.S. 1134 : 1950 and finally to adjust the meter to give this reading. The adjustment should then hold for all other specimens coming within the pass band. Because of the effects of the prescribed attenuation, however, the reading of a meter calibrated as described may differ slightly from the value determined graphically when the dominant spacing comes close to the cut-off: in such cases it is generally practical to accept the meter reading as the final arbiter. Successive magnification ranges, and the linearity of each range, are checked either by direct electrical methods or by the further use of gauge blocks. At high magnifications, however, the required step between the gauge blocks can become too small to provide useful accuracy, and it is then preferable to use a larger step and reduce it by means of a lever having a properly designed ligament hinge.

In the workshop the procedure can be greatly simplified by means of ruled standards which have been calibrated by interference methods or by a stylus instrument itself calibrated from gauge blocks. Such standards were first introduced by Dr. Tomlinson at the National Physical Laboratory, in the form of a row of etched grooves on a polished glass plate. The profile of a widely used grade is shown in Fig. 17.24 *a*. In America, C. R. Lewis and A. Underwood (Chrysler Corporation and General Motors) have evolved a ruled metal test specimen known as the "Caliblock" having a zigzag waveform of 150° included angle, which is reproduced by electro-forming (Ref. 27). The profile of a reproduction is shown in Fig. 24 *b*.

Calibration standards are generally marked with the value that would be obtained by measurement of the profile revealed by an interference microscope or by a stylus with a very sharp tip. Instruments with relatively blunt tips may give higher or lower values according to the shape of the profile and the radius of the tip (Ref. 31), and some allowance for tip effect will then have to be made. For general purposes, however, it is simplest to use a ruling so proportioned that tip effects are negligibly small and do not need to be considered. In the case of average readings, the crest spacing of the ruling should come well within the pass band of the instrument, so that calibration is carried out on the level portion of the transmission characteristic, and it is desirable also that the shape of the profile should bear some resemblance in harmonic content to that of the mechanical surfaces that will afterwards be measured, in which respect the shapes shown in Fig. 17.24 have been found satisfactory.

An important test too often overlooked, is to see how the instrument behaves on a well polished optical flat free from visible scratches. Any departures of the profile graph from a straight line, or of an average reading from zero, can be regarded as errors in the instrument. In the case of the average meter, it is rare to find a reading of less than a fifth of a micro-inch. Residual ripple from the mains, vibration or jerks from driving units or from the hand, may build up the reading to many times this value. The value obtained is a good guide to the smoothest surfaces that can be accurately measured or compared. Resulting from the laws of combination of alternating currents, the minimum average reading that can usefully be considered is about *twice* the reading on the optical flat which is then neglected. Below this the output from the optical flat becomes dominant. It cannot be allowed for simply by subtracting its value from the reading for the surface (Ref. 2).

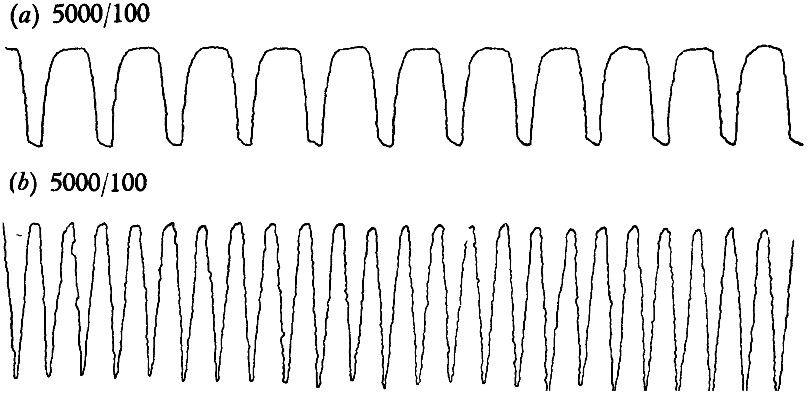

Fig. 17.24. (*a*) NPL-type etched standard. (*b*) Caliblock

OBLIQUE CROSS-SECTIONS AND TOPOGRAPHIC CONTOURS. *The Interference Method.* The optical principle (Ref. 5) is shown in Fig. 17.25. *Z* is the surface to be tested, *O* an optical test plate. A beam of collimated monochromatic light of which *p*, *q* are rays is reflected by the flat under-surface of the test plate and partly by the surface of the specimen.* After reflection the beams re-combine; but because of the separation of the surfaces, the beam reflected from the specimen will lag in time, and hence in phase, behind the beam from the test surface. There will therefore be a series of critical planes 1, 3, 5, 7 . . . 2, 4, 6, 8 . . . . for which the phase shift is respectively an odd or even multiple of 180°, the former leading to minimum and the latter to maximum brightness of the re-combined beams.* If the specimen Z is not flat, or is inclined to the test plate, the intersection of each critical plane with the surface under test will trace a contour line which will be either bright or dark. Suitably viewed, and selecting one or the other, the eye will therefore see a simple contour map of the surface, and these contours will be separated almost exactly by 0·00001 in. The effect will be most marked when the two beams contribute equal energy to the interference pattern, a condition which can often be secured by partially metallizing the under-surface of the test plate.

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* The diagram neglects the law of reflection.

For examining the general shape of the surface, there is needed at most the simple arrangement shown in Fig. 17.25*b*. For viewing the scratch marks some degree of magnification is required and a microscope is focused on the surface. One arrangement suitable for low powers is shown in Fig. 17.25*c*. The reference plate O is then very slightly inclined to the surface, with the line of intersection approximately at right angles to the direction of the scratch marks. The resulting interference fringes trace *Oblique Sections* of the texture. The separation of successive fringes again represents a depth of 0·00001 in., assuming that the normal cross-section of the scratches remains constant from one fringe to the next.

A micro-interferometer permitting the use of high aperture objectives (N.A. 0·58) has been derived from the Michelson interferometer by Professor Linnik. The principle is shown in Fig. 17.25*d*. Very high resolving power approaching 0·00002 in. spacing of the scratch marks can be secured.

More recent constructions due to Mirau and Dyson are shown in Figs. 17.25*e* and *f*. In each case the reference surface is a small silvered patch on one of the flat surfaces of the objective system. The reflecting objective of Dyson lends itself to higher numerical apertures than does the elegantly simple arrangement of Mirau.

The Hilger and Watts Surface Micro-Interferometer shown in Fig. 17.26 is of the kind shown in Fig. 17.25*d*, but has a rather different lay-out and a number of refinements including a choice of reference surfaces of different reflectivities to match that of the specimen and thus secure maximum contrast. An example of fringes seen through the eye-piece is shown in Fig. 17.27*a*.

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* Differential phase changes at the surface, which have to be assumed constant, are here neglected.

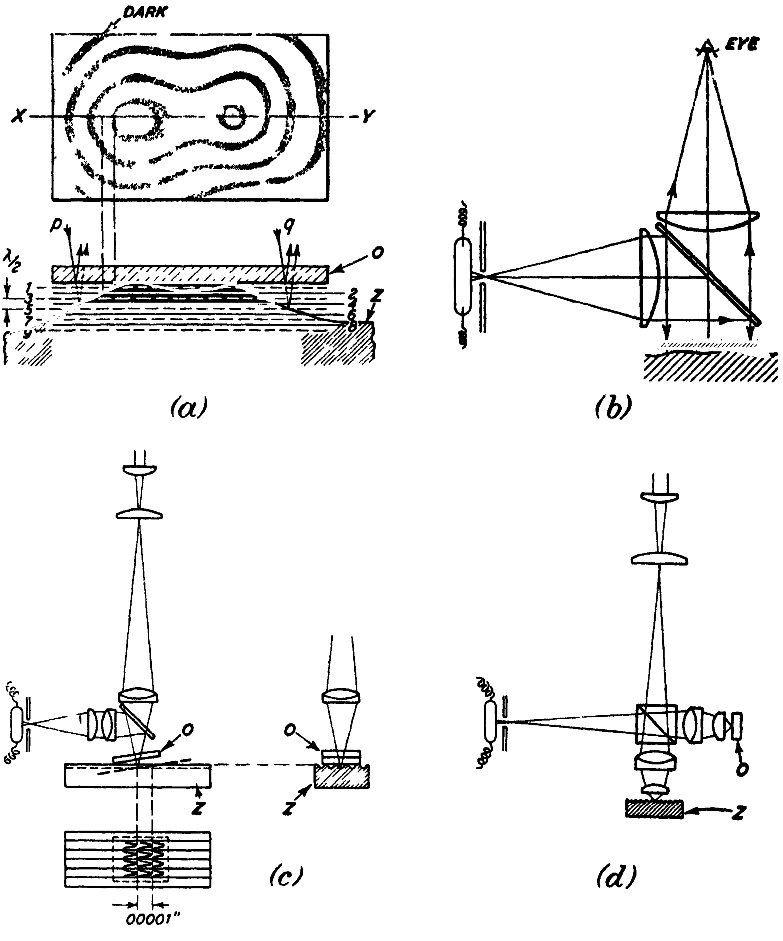
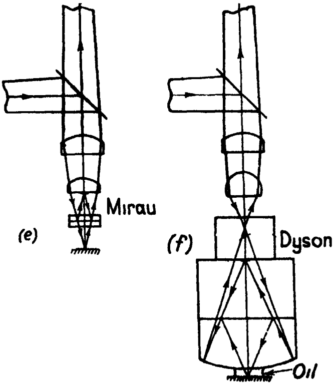


Fig. 17.25. (*a*) Contours by optical interference method. (*b*) Simple interferometer for very widely spaced irregularities (general errors of shape). (*c*) Principle of simple-micro-interferometer having low to medium aperture objective for examination of scratch texture. (*d*) Principle of Linnik micro-interferometer having high aperture objective. (*e*) Principle of Mirau interference microscope. (*f*) Principle of Dyson interference microscope



A method of reducing the width and increasing the sharpness of the fringes by permitting multiple reflections to occur between the specimen and the reference surface has been highly developed by Professor Tolansky (Ref. 32), and instruments incorporating the principle can now be obtained. The reference surface has to have a high coefficient of reflection and be placed close to the specimen, so that the basic form shown in Fig. 17.25*c* has to be employed, unfortunately with the restrictions on aperture and resolving power

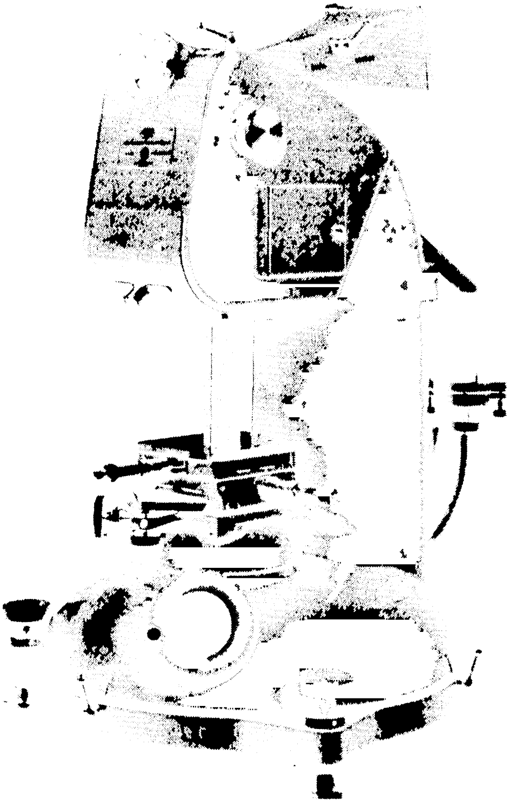


Fig. 17.26. Hilger-Watts Surface Micro-Interferometer checking 4″ gauge block

that this construction involves. An example of the multiple interference fringes seen through the Hilger and Watts Surface Finish Microscope is shown in Fig. 17.27*b*. Such instruments find useful application in the measurement of fine scratches less than 0·0002 in. wide, below which the commercial 0·0001 in. stylus begins to fall off. The range in depth can be extended by using a transparent replica of the surface immersed in a liquid having a refractive index approaching that of the replica.

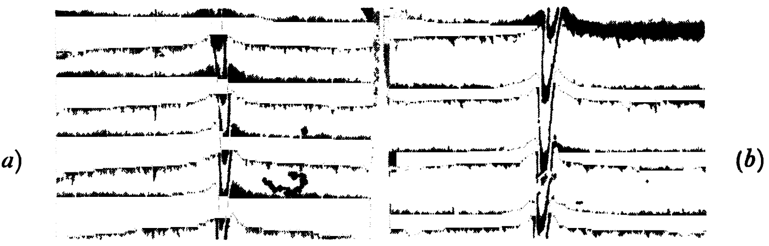


Fig. 17.27. (*a*) Example of 2-beam interference fringes on surface of slip gauge × 78. (*b*) Example of multiple-beam fringes on same slip gauge × 70

Although the wave-length of light has fundamental accuracy as a unit of length, the practical exploitation of this property in determining the true depths of the irregularities involves a number of considerations.

Firstly the micro-interferometer reveals fundamentally an oblique section which is seen projected into a plane normal to the surface, and the assumption is made that the cross section of the scratch marks remains constant throughout the portion of the surface lying between one fringe and the next. While the normal and oblique sections should be strict projections of each other in the case of ruled surfaces, there are many others, especially the abraded surfaces, for which the details in the two sections are often not the same, because of the rapidly changing texture of the rupture marks.

Then the scratches must not be too narrow compared with the wave-length of the light: it appears that the full theory of what happens to the fringes as the crest spacing approaches and finally becomes less than the resolving power of the microscope has still to be worked out.

A correction is also required for the obliquity of the marginal rays entering the objective, the obliquity tending to make the scratches seem deeper than they really are. The correction amounts to about 3 per cent for an objective of NA 0·3 to about 12 per cent for NA 0·65 (Ref. 48).

In the limit the question must arise of what is to be regarded as the true profile of the surface, for fundamentally the determination of where any part of a surface lies is dependent on the method used for locating it. Suppose, as an arbitrary starting point, that a geometrical surface containing the nuclei of the outermost atoms is considered to represent the real physical surface. In the interference method it is found that the light behaves as though it penetrated some distance below this surface before being fully reflected, the amount (often in the order of a micro-inch) depending on the physical structure of the material and being not necessarily the same for all points on the surface. To minimize this effect, surfaces are sometimes coated with an evaporated layer of silver before being examined. In the stylus method, for comparison, the stylus will sink below the real surface elastically or even with plastic deformation, generally by a greater amount again depending on the structure of the material. Thus apart from questions of resolving power and uniformity of texture, the two methods can give the same result only if the difference of penetration under operating conditions is the same for all points along the explored part of the surface.

The Taper Section. Another method of obtaining an oblique section is to cut what D. R. Nelson (Ref. 26) has called a taper section, that is, one slightly inclined to the surface. Burrs are avoided by first plating the surface with a metal of contrasting crystalline structure. If the section is polished and etched, the crystal structure just beneath the outer surface can be studied at the same time as the profile—a valuable feature. The method is often used in laboratories and very fine results have been obtained, but of course the method is destructive.

Other Methods. The earliest stylus instruments used a beam of light reflected from a tilting mirror, but were limited by the inertia of the mirror. (Refs. 6, 7, 8.)

The Schmaltz light-section method (Refs. 7, 9 and 33) has been developed by Professor Tolansky but still has rather a limited field of application: it is too insensitive for the finest specimens and its field of view is too small for rough ones. Various optical methods which have been tried in France are described by Michalet and others (Ref. 10).

The geometrical structure of very fine details is being strikingly revealed by the Electron Microscope as already exemplified in Fig.

17.4. Specimens small enough to go between the electron lenses can now be examined directly at grazing incidence; in other cases replica methods are used.

The Numerical Assessment of the Surface. KINDS OF MEASUREMENT. Of the many aspects of the irregularities which might usefully be measured, the one which has seemed to warrant first consideration is the height. If successive irregularities were uniform in shape and the crests lay all on the same level there would be no problem in height measurement—one would simply measure the height from peak-to-valley. Unfortunately most surfaces are irregular, and since it is generally undesirable to rate the surface on the basis of the highest peak and deepest valley, some method of averaging becomes necessary. It will be worth while to examine several of the many methods which have been proposed, if only to put the one or two that are commonly used into proper perspective.

All the methods so far proposed have in common the determination of a reference line relative to which the variations in level are measured. In most systems the shape of the reference line is defined independently of the irregularities as that of the nominal shape shown on the drawing, but in a more recent German proposal the shape of the reference line is determined by the irregularities themselves and is not open to independent definition.

Peak-to-valley Measures. A method defined in the 1952 D.I.N. Standards 4760 and 4762, and widely practised on the Continent where for a long time graphing instruments preponderated, is to assess the height as the separation of two reference lines respectively touching the highest peak and the lowest valley occurring within a given length of surface. This over-all height is known as the Rautiefe. Unfortunately, since the observer is expected to ignore any peaks and valleys that he deems to be exceptions, the assessment is sometimes uncertain.

A Swedish method based on peak and valley intercepts, which excludes the exceptions systematically, is shown in Fig. 17.28*a*.

In another systematic method described in B.S. 1134 : 1950 the mean difference is taken between the five highest peaks and the five lowest valleys. This has been called the 10-point height.

Mean-line Measures. In another group, shown in Fig. 17.28*b*, a mean-line is first established as a reference from which an integrated average of the whole of a defined length of the profile is obtained. The mean-line has the nominal shape of a defined length of the surface, and is so positioned that the sum of the squares of equally spaced ordinates measured from it is a minimum. This line is unique and its position can be calculated, but the calculation being sometimes tedious, it is generally determined as one parallel to the general direction of the profile for which the areas embraced by the profile above and below the line are equal, in which form it is called the *centre-line.* When the wave-form is repetitive the two definitions are precisely equivalent, but when it is irregular the latter definition calls for personal judgement in assessing the "general direction". The mean-line is found automatically by electrical integrating instruments.

From the mean-line can be measured either the arithmetic average departure of the profile taking all ordinates as positive, or the root-mean-square value which is generally 10 per cent to 30 per cent greater according to wave-form. The basic formulae are given in the figure. Both the 1950 British Standard 1134 : 1950 and the 1955 American Standard B. 46/1955 are based on the former, the quantity being called the centre-line-average (c.l.a.) value in the British Standard and the arithmetic average (a.a.) value in the American Standard.*

Crest Line Measures. In yet other methods (used on the Continent) the average distance of the profile from a datum contacting the highest peaks or lowest valleys is measured, the former (Nicolau's method) being shown in Fig. 17.28*c*.

In the recent proposal shown in Fig. 17.28*d*, Dr. H. von Weingraber has suggested that the crest line should be determined as the locus of the centre of a circle of defined radius rolling across the surface, the locus being displaced towards the surface until it contacts the crests (Ref. 34). This method, with a radius for the rolling circle of 25 mm., has been tentatively standardized in Germany (D.I.N. 4760, 4762 : 1956)† where it is known as the *E* (envelope system), in distinction to the *M* (mean-line) system. The average depth of the profile below the contacting envelope is known as the *G* value (Glättungstiefe, or levelling depth). If the envelope line is displaced still further so that the areas enclosed by the profile above and below it are equal, the separation of the two lines is equal to the value of *G*. The depth of the deepest valley below the envelope is taken as the total height (Rautiefe).

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* Before 1955 the American Standard was based on the r.m.s. value.

† It is important to realize that the 1956 (envelope) versions of these standards continue to use many of the same terms and symbols as were used in the 1952 (mean line) versions, but with the altered significance resulting from the change in the definition of the reference line. As far as is known (at the time of printing) all German instrumentation refers to the 1952 standard.

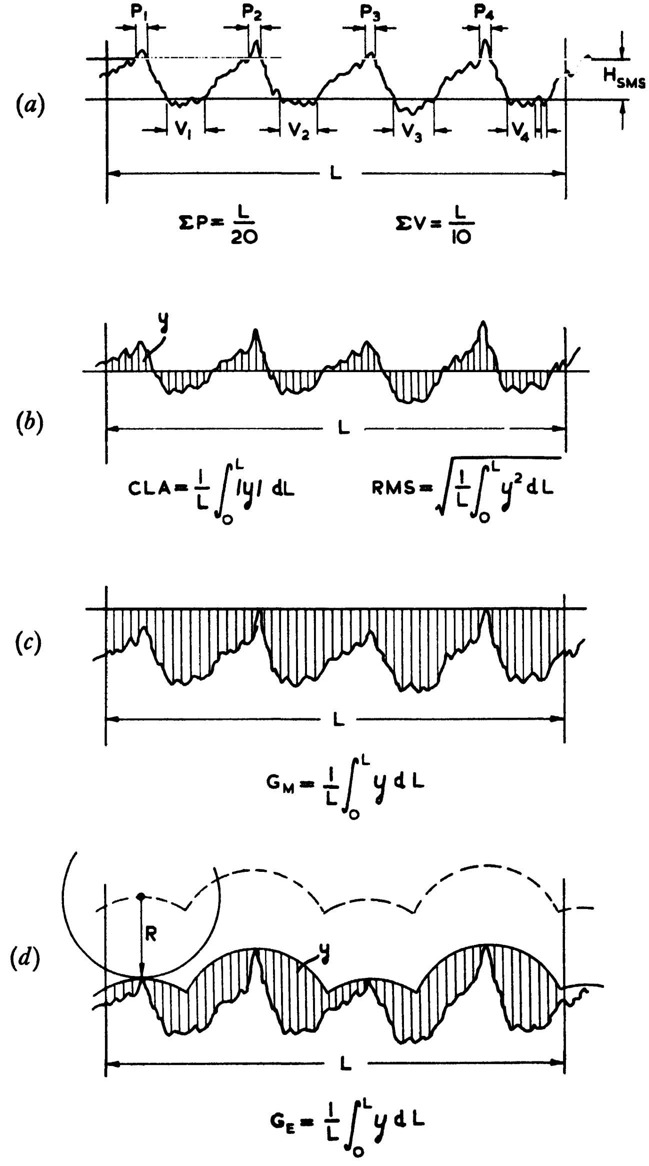

Fig. 17.28. Methods of assessing average height: (*a*) Swedish peak-to-valley. (*b*) Mean-line methods (c.l.a. and r.m.s.). (*c*) Crest-line method. (*d*) Envelope method (von Weingraber)

Applied to the profile graph, the rolling circle must be scaled up, vertically and horizontally, in the same proportions as the profile. For unequal magnifications the resulting shape is strictly eliptical, but in practice a circle having the radius of the elipse at its vertex can generally be used. If R is the radius of the circle rolling on the specimen, the radius to be used for the graph is

$$\frac{R\,M_H{}^2}{M_V},$$

where M_H and M_V are the horizontal and vertical magnifications. Thus for a horizontal magnification of 100, and a 25 mm. rolling circle, the radius will range from 10 in. to 0·2 in. as the vertical magnification rises from 1,000 to 50,000.

The definition leads to difficulties when the surface is curved, for the locus of the rolling circle then has no longer to be displaced bodily but to be expanded or contracted radially from the centre of curvature of the surface, the position of which centre may not be easy to establish. Further, in the case of concave surfaces, the radius of the rolling circle must be less than that of the surface, and there will be many surfaces, for example the tracks of ball races, to which the standardized circle of 25 mm. radius could not be applied. In practice, however, instrumental means for eliminating the curvature of the surface have always to be used in order to hold the profile of a reasonable length of surface on the paper, and therefore it is to to this that the concept of the 25 mm. radius really applies. Strictly, it would seem that the fundamental definition should be given in terms not of radius but of difference of curvature, that is if r is the radius of the surface and r_e that of the rolling circle,

$$\frac{1}{r_e} = \frac{1}{r} + \text{const.}$$

For the 25 mm. basis, the constant would be unity for radii expressed in inches, and 0·04 for radii expressed in millimetres.

SELECTION OF THE IRREGULARITIES TO BE MEASURED. Since the basic concept of surface texture excludes errors of form, all methods of numerical assessment must in some way be made selective. Very often the requirement is to distinguish not only between texture and form, but between different kinds of texture—even between the rupture marks and tool marks of the primary texture.

Selection by Length of Sample. In the case of methods involving a reference line of pre-determined shape, selection is accomplished fundamentally by basing the measurement on a sample of the surface of defined length. It will be seen in Fig. 17.28 that computation of all the measures from *a* to *c* involves the length *L*. This is called the "sampling length" in B.S. 1134: 1950 and the "roughness width cut-off" in B.45–1955; all irregularities within it are included in the measurement, while those of appreciably greater spacing are left out of account. Desirably, several samples are evaluated (electrical instruments indicate the mean of several taken consecutively) to eliminate point to point variations, but this does not alter the fact that *L* is the basic length determining the selectivity. The *total* length of surface taken into account (i.e. the sum of all the samples) is called the "traversing length" in B.S. 1134 : 1950 and (with unfortunate confusion) the "sampling length" in B. 46–1955.*

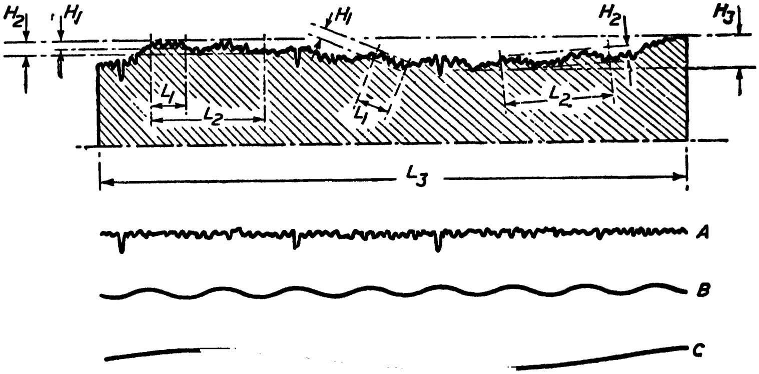

Fig. 17.29. General case of scratch texture A, vibration texture B of about the same height, and error of shape C, in combination on a single surface. The assessment of height depends on what length of surface is taken for measurement from a continuous datum line

When the profile is reasonably repetitive in shape, the value chosen for *L* for a graphical determination should properly be a whole number of wave-lengths (or occasionally half or quarter wave-lengths) unless enough are included for terminal considerations not to matter. Such wave-forms, with a wave-length equal to the traverse feed, commonly result from single point cutting processes.

In the case of abraded surfaces, there is no regular spacing to determine the proper sampling length, but there is generally a quality of uniformity suggesting that if measurements were to be made with a progressively increasing sampling length, a value would be reached beyond which any increase (in the absence of secondary texture and errors of form) would lead to no further increase in the assessment of the height. This value is generally to be found in the region between 0.003 in. and 0.03 in., and the latter figure, in the absence of special considerations, has come to be accepted as the proper sampling length for such surfaces.

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* These terms are being reconsidered with a view to meeting the situation.

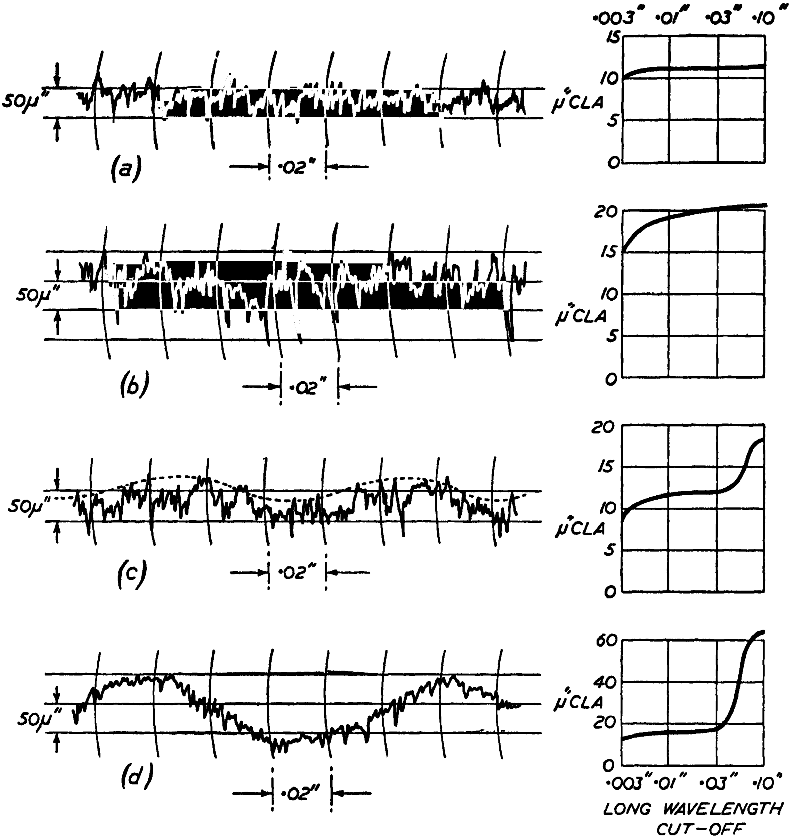


Fig. 17.30. Graphs of four surfaces, and to right of each, centre-line average value plotted against long-wave-length cut-off value of measuring instrument

The general case including secondary texture and error of form, is shown in Fig. 17.29. A short length L_1 will serve to isolate the primary texture and give a value (peak-to-valley for simplicity) of H_1; if the length is increased to L_2 the wave will be included and the value will rise to H_2; if the whole length of the surface is included the total height will be H_3. Of all the values of H that can be found, however, only those corresponding to L_1 or L_2 will relate to specific aspects of the texture.

Although the values H_1 and H_2 are nominally the same no matter where the appropriate sampling length is situated, in practice there may be variations both from end to end and between adjacent samples. The former may need to be taken into account but the latter should be averaged out by taking a number of adjacent samples.

In electrical instruments, the equivalent of the sampling length is provided by the cut-off wave-length, which is made numerically equal to the intended sampling length. In contrast to the graphical method, however, it is not necessary that the cut-off wave-length should be an exact multiple of the crest spacing of a periodic waveform: it needs only to be as great or greater.

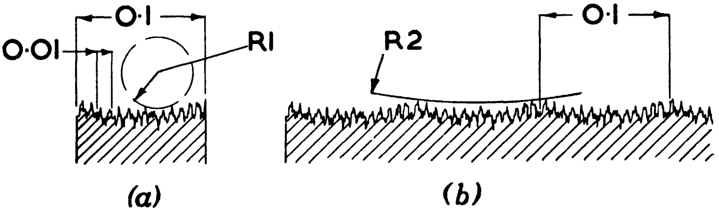


Fig. 17.31. Demonstration of need for analytical selection of irregularities to be measured

For instrumental convenience, sampling lengths have been standardized in the series 0·003 in., 0·01 in., 0·03 in., 0·1 in., 0·3 in.

The rate at which the height value increases with increase in sampling length for four representative ground surfaces, is shown in Fig. 17.30, alongside the corresponding profile graphs. For convenience an electrical instrument having cut-off values (sampling lengths) of 0·003 in., 0·01 in., 0·03 in., and 0·1 in. was used. The measurement of *a*, which has no significant texture of greater spacing than 0·01 in., is but little affected by the value of the cut-off, as might be expected. In *b* the reading increases up to 0·01 in. cut-off and is then steady. In *c* the 0·01 in. and 0·03 in. values again give about equal readings (a very common finding), but the distinctly visible undulation indicated by the dotted line causes an increase for the longest step. *d* should speak for itself.

A demonstration of the need for selection for different types of specimen is given in Fig. 17.31, which shows diagrammatically (*a*) the whole width of a turned piston ring, and (*b*) on the same scale, part of a larger shaped surface. In the case of the piston ring, it was necessary to distinguish between the tool marks (the primary texture) and the general curvature, both of which were separately specified. On the basis of the dimensions shown, a sampling length of 0·01 in. would serve to measure the tool marks while ignoring the curvature. In the case of the shaped surface, however, the tool marks alone, which constitute the primary texture, have a spacing and curvature comparable with the whole width of the piston ring, and call for a sampling length of at least 0·1 in. Clearly it would be impossible to measure the primary texture on each of these surfaces with the same sampling length.

Selection by Radius of Rolling Circle. In the German envelope method, the selection of what is included in the measurement is determined by the radius of the rolling circle. Applying this to the surfaces in Fig. 17.31 it will be seen that a radius R_1 will serve to separate the tool marks from the general curvature of the piston ring, while a much greater radius R_2 will be needed to measure the tool marks on the shaped surface. Clearly, if the radius R_2 were used for the piston ring the curvature would inevitably be included in the measurement, while if the radius R_1 were used for the shaped surface, the measurement would be limited to that of the rupture marks.

Although the radius of the rolling circle plays a part analogous to that of the sampling length, it should be noted that its discrimination is dependent on the amplitude as well as the spacing of the irregularities, whereas that of the sampling length is dependent on spacing only.

It seems that the envelope method, if introduced, will call for a series of radii, similar to the series of sampling lengths needed by the mean-line methods.

PROPERTIES AND COMPARISON OF METHODS. All methods of measuring the height so far advanced are arbitrary in the sense that they bear no direct physical relation to performance: they serve only for comparing one piece with another made by the same process. Investigation has shown that in this respect there is little to choose between them. They give no indication of the shape of the profile, and profiles very different in shape may have the same average height. While the mean-line method has a formal mathematical derivation, the other methods are arbitrary in this sense also.

It is often felt that peak-to-valley measurement would be significant in connection with fatigue strength; but it has to be remembered that apart from weaknesses caused by subcutaneous defects in the crystal structure it is the shape as well as the depth of the scratch that counts.

The Swedish method of averaging the peaks and valleys has the merit of indicating directly the dimensional change that would result from lapping off the bulk of the scratch marks. The British "ten-point height" method was conceived mainly as a possible aid to the quick assessment of interference fringes seen through a microscope. Neither of these methods lends itself to direct-reading instrumentation.

An investigation by Professor P. Diachenko in connection with the I.S.O. Standard showed that for a variety of common surfaces the ratio of the Swedish height to c.l.a. was around 4, while that of the ten-point height to c.l.a. was around 5.

The centre-line methods lend themselves to simple direct-reading instrumentation. The c.l.a. value is best regarded simply as an index (somewhat akin to a hardness number) by which a defined manufacturing process can be rated and controlled. Evidence of the ability of the c.l.a. index to serve this purpose is to be found in Ref. 35 (Ebsworth). A proposal of Mr. de Vries to use the term "ru" (pronounced roo) for the unit of c.l.a. measurement (x ru $= x$ micro-inches centre-line-average) has much to commend it as a workshop device but may need a metric counterpart.

The G value can generally be determined from a profile graph more readily than the c.l.a. value, but direct-reading instrumentation appears to be difficult because of the impossibility of arranging the skid and stylus to act simultaneously along the same normal to the surface, as the basic method demands. Separation of the skid and stylus leads instrumentally to approximation or complication.

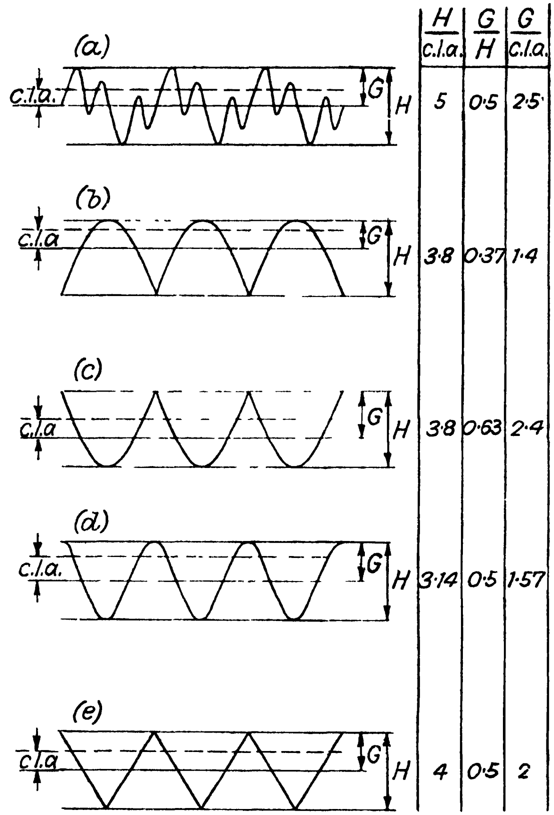
One useful criterion for comparing the ability of any two methods to convey information about the worth of parts or the behaviour of processes, that can be applied without functional experiment, is the extent to which they are convertible by means of a factor or formula. If completely convertible, there is no information that can be conveyed by the one that cannot be conveyed by the other. Of the methods so far suggested no two are exactly convertible, though some are reasonably convertible at least for a given process. For one example, the ratio of r.m.s. to c.l.a. is generally between 1·1 and 1·15 for turned surfaces, between 1·15 and 1·2 for ground surfaces, and around 1·3 for lapped surfaces. For another example, while the ratio of *G* to c.l.a. can theoretically vary from ½ to infinity. Dr. von Weingraber found ratios only between 1·85 and 3·0 for a wide range of surfaces extending from lapping to shaping (Ref. 34). For the ordinary range of grinding, the ratios extended only from 1·8 to 2·6 with a mean at 2·4—a figure confirmed independently in the Taylor-Hobson laboratory. Remembering that acceptable ground surfaces commonly vary by ± 15 per cent from place to place, and by 2:1 throughout a batch, the significant information conveyed by *G* value would, as far as these results go, differ but little from that conveyed by the c.l.a. value.

Another consideration is the extent to which the method reflects the degree of rounding of the crests for equal total heights. The crest line measures tend to give a smaller value for rounded than for pointed crests (compare Figs. 17.32*a* and *b*). The Swedish method has a slight power of discrimination (because the arbitrary peak and valley line percentages are not the same); the mean-line methods have no such power.

In some cases information about the degree of rounding can be conveyed by what are generally, though not well, described as "form factors".

The nature of three possible factors is shown in Fig. 17.32. When the peaks and valleys are symmetrical as in Fig. 17.32*a*, the mean line is midway between the peak and valley lines and the ratio of $G/H = 0{\cdot}5$. In Fig. 17.32*b* where the crests are more rounded than the valleys, it moves up, while in Fig. 17.32*c*, which is the inverse of Fig. 17.32*b* it moves down. Here, therefore the ratio of G/H throws light on the question of shape. However, it would not distinguish between Figs. 17.32*d* and *e*. The shape of these figures could be distinguished by considering the ratio H/c.l.a., which would be greater for Fig. 17.32*e* than for Fig. 17.32*d*, but this ratio would not distinguish between 17.32 *a* and b. Thus both of these well-known factors would have to be taken into account before the shape of the crests could be deduced. A more useful factor might be their product, that is, the ratio of G/c.l.a., which is seen to become smaller as the crests become more rounded; unfortunately, the change in its value in relation to the degree of rounding is sometimes too small to be reliable (compare Figs. 17.32*b* and *d*).

The illustrations in Fig. 17.32 are confined to repetitive waveforms, for which the proper position of the crest and valley lines is in no doubt. When the profile is irregular it becomes necessary to introduce an artificial rule for where to position them; and, despite the many years through which the various factors have been discussed, a sound and universally acceptable rule has still to be found. The resulting numerical uncertainty has been sufficient to mask the possible significance of the factors themselves. In practice, remembering that the shape of the profile is often a natural consequence of the process, careful study might be needed before a numerical specification of the degree of rounding could be justified economically.



	H/c.l.a.	G/H	G/c.l.a.
(a)	5	0·5	2·5
(b)	3·8	0·37	1·4
(c)	3·8	0·63	2·4
(d)	3·14	0·5	1·57
(e)	4	0·5	2

Fig. 17.32. Comparison of shape factors

Bearing Area Measures. If, under zero load, a nominally flat surface is placed in contact with one assumed perfect, kinematic principles indicate that initially not more than three of the highest points can actually be touching. When a load is applied, the areas of contact spread out under elastic and eventually under plastic deformation, and further points come into contact. Bowden and Tabor (Ref. 36), using electrical resistance and other methods, have shown that the total area of real contact is proportional to the load, thus accounting for the laws of friction. The principle holds even for well-lapped surfaces.

The initial points of contact can also be expanded by progressive lapping representing wear, the area of real contact then being that in contact with the lap.

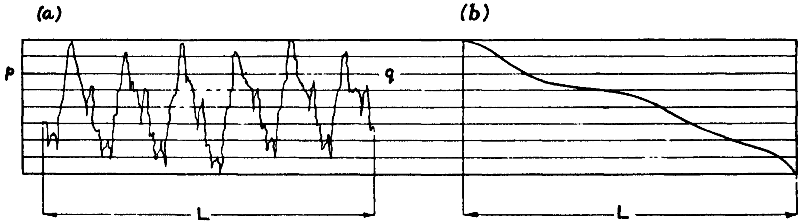


Fig. 17.33. The Abbott-Firestone 'bearing area' curve

In each case the area of real contact is called the bearing area.

An estimate of the bearing area is often derived from a profile graph by drawing a line such as *p q* in Fig. 17.33*a* equidistant from the reference line and measuring the sum of the metal intercepts along its length. Making the generally invalid assumption that the profile extends uniformly across the surface in the direction normal to the section plane, the proportion of the intercepts to the length of the line will indicate the proportion of true to apparent bearing area that might be expected after a given amount of lapping. The position of the bearing line is often defined in terms of its distance below the extreme peaks expressed as a fraction of the total height, and thus involves the problem of defining the total height in a satisfactory way.

From measurement of the intercepts along a number of bearing lines Abbott and Firestone obtained their well known "bearing area curve" (Fig. 17.33*b*) which gives an indication of the rate at which wear may be expected. Ehrenreich (Ref. 38) has suggested that the slope of the curve could provide a useful index of performance.

A visual estimate of the bearing area under load has been obtained by pressing the surface against the reflecting face of an internally reflecting prism (Fig. 17.34). Reflection is destroyed wherever there is contact, these areas appearing as dark patches in a bright field. The prism must be hard enough to withstand the abrasion, and its refractive index must be high compared with that of oil, otherwise the reflection would be stopped as readily by residual grease films as by the metal-to-prism contacts. Diamond appears to be the only material that satisfies these requirements, but its high cost sets a limit to the maximum length on which the bearing area can be assessed. In the Visoport instrument* the length is 2½ mm. The conditions of load have to be standardized in a satisfactory way. In the Visport instrument it is varied according to the elastic modulus of the material being tested.

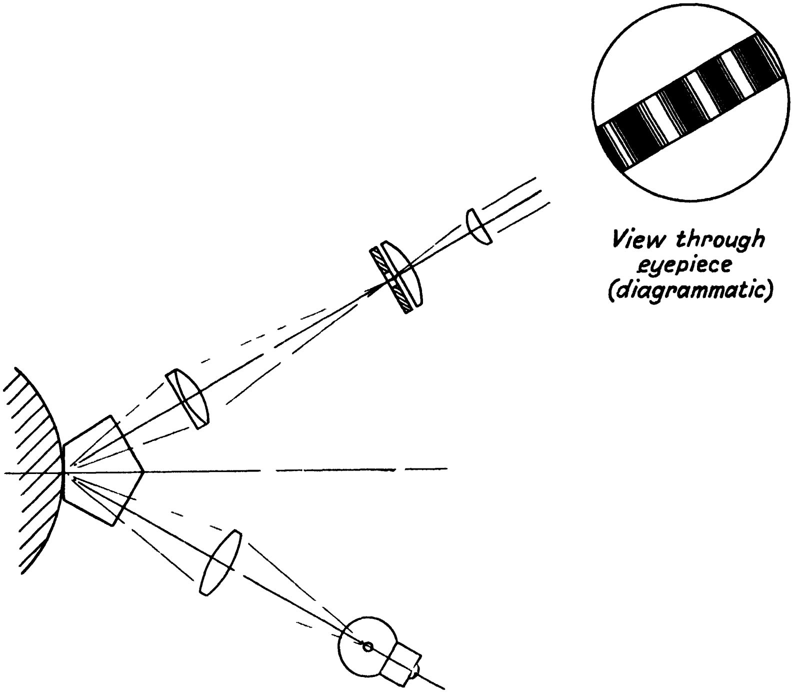


Fig. 17.34. Internal reflecting prism method of assessing bearing area (used in Visoport instrument, Kordt and Co.)

Specification of Texture. For a complete specification (as far as completeness is now recognized) it is necessary to state the process to be used (e.g. grinding, turning lapping, etc.) in adequate detail, and add to it a controlling index. The index itself will involve the cut-off wave-length (or the radius of the rolling circle if this system is used) which must be specified either by implication or by statement together with the number obtained, as without this knowledge no kind of height number relating to an irregular surface has any real meaning.

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* Kordt and Co.

There should, however, be no great difficulty in deciding which sampling length to choose. Firstly, until a great deal of experience has been acquired, every specification that is worth anything will be derived not from fancy but from the measurement of a master part typical of one whose fitness for the job has been established by experiment and worked out in terms of the method of making it, so that the proper characteristics of the measuring instrument will be settled naturally by what exists to be measured on this part. Secondly, the proper value for the cut-off is often found to be in fairly close relation to the type of finish. For example, for lapped, diamond tooled, and commercially fine-ground surfaces, which constitute perhaps 90 per cent of those normally controlled, a sampling length of 0·01 in. or 0·03 in. is generally reasonable. But where a wide range of surfaces must be covered, and for basic experiment, a choice of cut-off values is evidently desirable.

Since a well-founded specification will reflect the performance under test of surfaces machined in a particular way, it would generally be wise to assume that the long wave-length cut-off associated with the CLA value, whether stated directly or by implication, represents the maximum permissible crest spacing, or traverse feed in the case of cut surfaces. There has, however, been no formal ruling on the point, and if a greater spacing were deemed satisfactory, a correspondingly greater cut-off value would have to be used to ensure a full CLA reading.

Sometimes it is thought that better control could be exercised, and reference to process avoided, by specifying a group of numbers representing height, shape and bearing area. It is the process, however, that determines both the texture and the metallurgy of the surface, and care would have to be taken to see that specified sets of figures conformed with the general characteristics of a practical process, for if they did not there would be serious interference with production. On the other hand if they did, their helpfulness compared with that of an adequate statement of process could well be questioned, for while statements of process can be irksome, the interpretation of a group of numbers could be even more so.

Other Measures. Lack of space reduces mention of other methods to name and reference. Perthen (Ref. 11) and Nicolau (Ref. 12) have devised instruments for measuring the average depth from a reference surface contacting the crests, the former by electrical (capacitance) means and the latter by a pneumatic device, an unfortunate limitation of both being that on curved surfaces changes in curvature resulting from dimensional tolerances cannot be distinguished from changes in texture. Proposals have been made for assessing the average slope (Fleming, Ref. 13), and the degree of polish or lustre (Guild, Ref. 16). The Anderometer* is in use for assessing the overall irregularities of an assembled ball race (Abbot and others, Ref. 17). A form of indentation hardness measure taking the scratch texture and the elastic constants of the surface jointly into account has been developed for use in ball-bearing manufacture (Törnebohm, Ref. 18).

The Use of Stylus Instruments. It is constructive always to look carefully at an unknown surface, and feel it, before testing it with an instrument. A low-power magnifier (watchmaker's eyeglass) may help, and if permissible and possible a single touch with a truly flat oilstone (the oilstone test) can be most revealing of widely spaced crests. These preliminary observations will quickly give a broad idea of what kinds of texture are present, and so help to avoid misusing instruments by applying them to surfaces for which they are not suitable. They can also lead to the building up of a realistic conception of what surfaces are like in their three-dimensional topography.

Having got a broad idea of what exists to be measured, some points to be taken into account are:

1. The most reasonable direction of traverse across the surface, bearing in mind that the instrument reveals and measures aspects of topography, rather than of function.
2. The maximum spacing of the crests in the proposed direction of traverse. From this is decided whether or not a skid can be used, and, if some kind of average reading is wanted, whether the instrument's selectivity is suitable. The latter applies also to the graph if the magnifying system (e.g. piezo-electric) is one not responsive to sustained deflexion of the stylus.
3. Which method of height assessment is to be used—c.l.a., or one of the peak-to-valley measures.
4. Useful accuracy.

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* Micrometrical Corporation.

It is quite natural to think that the proper direction of traverse is that in which the surface will slide on its mate, regardless of any directional characteristics of the texture. If the quantity being measured were "roughness" in a functional sense, this idea might be correct; but in relation to instruments measuring "roughness" solely in a topographical sense, it needs considerable qualification.

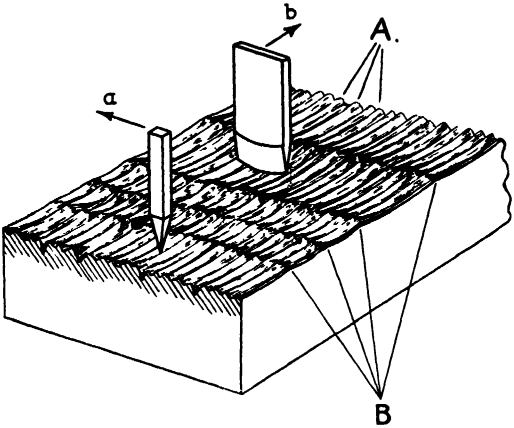

Fig. 17.35. Showing best forms of stylus, and best direction of movement, for measuring scratch marks A and chatter marks B

When using topographic instruments, the proper direction is determined entirely by the geometrical objective, which is to measure the height of the irregularities under discussion as efficiently as possible. Thus the scratch marks *A*, and the chatter marks *B*, of the diagrammatic ground surface shown in Fig. 17.35 should each be measured approximately at right angles to their length. Sometimes there will be occasion to measure the rupture marks within each scratch mark, and for this purpose a sharp stylus may legitimately be traversed along the scratch marks, but it will then be necessary to position the work with great care so that the stylus does in fact run along the crest or valley of a single scratch mark, as otherwise the profile of the rupture marks may be confused by secondary effects resulting from stylus climbing from one scratch mark into the next.

The two measurements cannot usually be made without some change in the instrument, for while in the example the scratches *A* obviously need a sharp stylus, the ripples *B* need a tracer which is blunt at least in the transverse direction in order to disentangle them from sundry residual effects of the scratch marks (Ref. 2). Furthermore, the length of traverse must be greater for the ripples than for the scratch marks, the horizontal magnification needs to be much less, and while a skid datum would suffice for the scratch marks, it would not suffice for the ripples.

Measurement obliquely to the direction of the irregularities will obviously not change their depth, but will increase their apparent spacing, perhaps enough to cause a low reading unless the instrument is modified accordingly.

It is generally practicable to measure slideways along and across the length (with suitable tracers), while cylinders can nearly always be measured parallel to the axis (for turning or abrasive scratch marks), and circumferentially for chatter marks and lobing. Widely spaced chatter marks (unless bad) can often not be seen, and lobes can never be seen, by preliminary visual or tactual inspection. These must be sought with the aid of an instrument, and the inspection must generally be continued right round the cylinder, perhaps by the methods described on pages 14–18.

It is important to be very clear about whether a measurement being made or discussed is a centre-line average (c.l.a.) value, or a root-mean-square (r.m.s.) value, or a total peak-to-valley value, or some kind of average peak-to-valley value. All are measured in millionths of an inch (1 micro-inch, 1μ in. = 0·000001 in.), the micro-inch being a unit of length that is not peculiar to any one method.

If a British scale-and-pointer instrument is used, it is likely to be scaled in c.l.a. values. American instruments formerly gave r.m.s. values which are from 10 per cent to 30 per cent higher than c.l.a. values according to wave-form, 15 to 20 per cent being a round figure for ground surfaces; more modern instruments give c.l.a. or both. When graphing instruments only are available the peak-to-valley value is often assessed in some way, and this may be four to ten times the c.l.a. value according to the nature of the surface and the method of assessment. Widely spaced irregularities (so-called "waviness") are nearly always measured from peak to valley—a point which must be sharply watched when comparing their height, say, with that of the scratch texture of a grinding process measured as a c.l.a. value. To avoid confusion it would be desirable to speak of the c.l.a. (or peak-to-valley) value, or reading, rather than of the "micro-inch reading" (as is so common), as in this country and in America it is the micro-inch that can more safely be assumed.*

In addition to being clear about the method of assessment, it is necessary to be clear about the sampling length. In current practice as laid down in B.S. 1134 : 1950 a value of 0·03 is to be assumed if no other value is stated or attached to the numerical value of the height. Thus there are three essential ingredients of an unambiguous assessment of height—the method, the sampling length, and the number itself.

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* On the Continent the metric unit of 1 micron (1μ) = 0·001 mm. = approximately 40 micro-inches (40 μ in.) is used. The prefix "Micro" is used to signify a millionth part of many quantities, e.g. micro-henry (μH), micro-farad (μF). The letter μ is used internationally by itself to signify a thousandth part of a millimetre, that is a millionth of a metre.

The use of so many methods of assessing the height, like the use of so many different wire gauges, is of course extremely undesirable, but for the present does not seem easily avoided. Even more measures may be introduced before finality is reached.

Regarding useful accuracy, quite large changes in texture often make comparatively little difference to the performance. For example, it is normal to find that acceptable aero-engine parts, ground in ordinary production, vary throughout a batch over a range of 3:1, and that a tolerance much closer than 2:1 would involve more rejects than is functionally justifiable. Differences of 10 per cent, therefore, would generally not be worth arguing about.

Surface Assessment in the Workshop. If figures relating to surface texture are to be given on drawings, the operator of the machine as well as the inspection department should be given the means to ensure that the product is to specification. Unfortunately this ideal is still not easy to reconcile with the present-day cost of surface meters, despite the progress that has been made.

A great deal has been accomplished on a quality control basis, one instrument centrally placed in a workshop then serving the needs of a good many machines. It is also possible sometimes, to make use of a measured sample as a link between the instrument and the machine. The provision of at least two such samples, one having the maximum roughness allowable, and the other perhaps half that amount, would often help the operator. In many cases the only kind of sample that is satisfactory is a specimen of the actual part, or a replica of it. Such specimens must be produced and stored by the manufacturer himself.

STANDARD ROUGHNESS SPECIMENS. It is sometimes possible to make use of what are often called "Standard Roughness Specimens". The basic idea is to have sets of specimens of convenient size, exhibiting various grades of texture produced by each of a number of different processes. These and the product are compared by sight and touch. Allowance may have to be made for differences in materials. Some sets, for example those shown in Fig. 17.36*a* and *b*, are produced in steel by direct machining, while others, for example the General Electric Company's set, consist of electro-

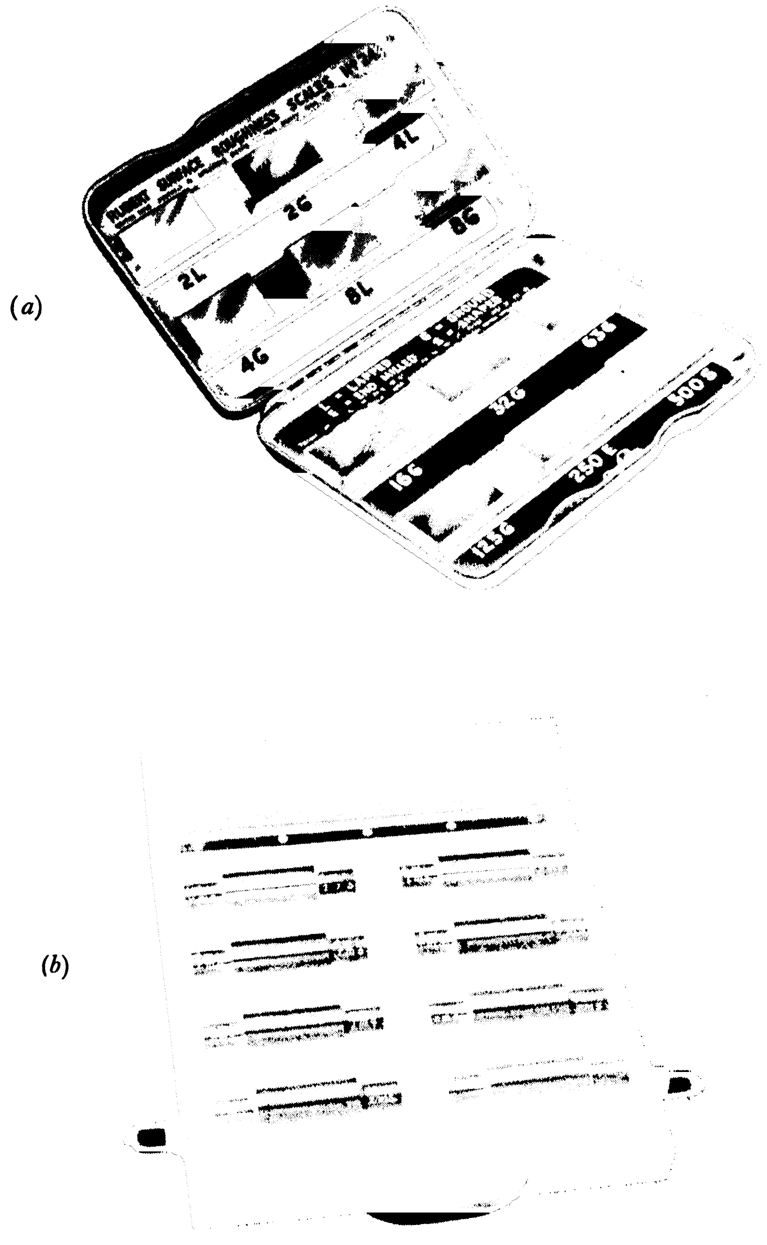


Fig. 17.36. Standard roughness specimens. (*a*) Rubert & Co.'s No. 24 set. (*b*) Norton Grinding Wheel Co.'s set

formed reproduction of "master" specimens. Generally the successive grades of texture of each process follow some part of the series 1, 2, 4, 8, 16, 32, 64, 125, 500, 1000 micro-inches centre-line average (or r.m.s.).

It would be an advantage if there were a standard specification to ensure that specimens of a given grade and process always looked alike, for although each make seems excellently self-consistent, there are sometimes considerable differences between different makes. A first move in this direction has been taken in B.S. 2634 : 1955, covering flat and cylindrical ground specimens. Having regard for the enormous variety of textures that can be produced by each process for each standard grade of height, it is not an easy problem; yet if these sets are to be referred to for example as between contractor and subcontractor the need for standardization is obvious.

Cast Replicas. Processes of obtaining cast replicas in a plastic material have long been known. The earliest Faxfilm process (U.S.A.) appeared to use cellulose acetate strip (cine film) softened with a solvent of unstated composition, which was pressed against the surface till set. Chisholm and Lickley (Ref. 19), Faust and Tolansky (Ref. 20), Pearson and Hopkins (Ref. 21), Timms and Scoles (Ref. 22) describe other processes in operative detail.

Useful results have been obtained from cellulose acetate sheet about $\frac{1}{8}$ in. thick. Pieces of suitable size—perhaps $\frac{1}{2}$ in. square—are cut, immersed in acetone for about 10 seconds, or coated with a cellulose solution containing a plasticiser, and quickly pressed against the surface under sufficient load to ensure contact. The replica can be removed within two or three minutes and is hard enough for the Talysurf after about fifteen minutes drying in air. When acetone alone is used the original surface of the sheet must be well finished as pits and scratches tend to get depressed into the surface of the replica rather than squashed out. About 80 per cent fidelity can be secured.

More modern materials approaching 100 per cent fidelity over a short length are found among the epoxy and other resins.* Generally a powder and a liquid have to be mixed in the correct proportions and poured onto the surface, from which the replica can be removed and used as soon as it has set. Setting may take from 10 minutes upwards according to material and temperature. Some sort of wall, e.g. a ring of plasticine, may have to be erected on the surface to contain the mixture.

* Examples of this kind of material are known under the trade names of "Crystic" and "Technovit". The Taylor-Hobson encapsulated dispenser kit may also be mentioned.

The question of whether a process will give a good enough replica for a given application can easily be checked by the user by comparing the profile graph of a sample part with that of its replica. It is important to make sure that exactly corresponding portions of the sample and of its replica are compared. This can often be accomplished by scribing a cross on the original surface with its arms at 45° to the intended direction of the trace, and letting the stylus pass through the intersection. If the stylus passes to one side or the other two disruptions, one from each arm of the cross, will appear. From their separation in two separated traces the intersection, appearing as a single disruption, can soon be found.

When replicas of the finer surfaces are wanted it is as well to check the process not only on the surface itself but also on an optical flat. Any irregularities which appear in the replica of the flat must be attributed to the replica process, and indicate the limit of smoothness for which the process is suitable. Random faults such as air bubbles can generally be neglected, but systematic irregularities resulting for example from shrinking effects or from grain due to a filler, must be reasonably small compared with the irregularities to be reproduced. It has been found that the residual granularity, waviness and setting time of the synthetic resins can be considerably affected by the wetness of the mix.

Replica processes can not only solve the problem of inspecting very large parts which cannot be brought to an instrument, but can also open up the possibility of issuing replicas of a master part, instead of standard specimens, as part of a surface specification.

FUNCTIONAL ASPECTS OF TEXTURE. Consideration of the functional aspect of surface texture should be accompanied by a lively regard for the many physical properties that come into play.

Most machining processes, apart from their topographic effect, give rise to high surface temperatures and stresses which modify considerably the crystalline structure of the outermost layers of the material, on which layers initial wear so greatly depends. Furthermore, oxygen in the air forms on most of the ordinary engineering metals, within a few seconds of cutting, an oxide film which Finch first showed to have a vital and often beneficial effect on friction and the mechanism of seizure. (Ref. 29.)

In the case of sliding members, there are always *two* surfaces to be taken into account, and it is not so much their individual properties as the relationship of their properties that matters. While they are ideally kept apart by a film of lubricant, contact from time to time is bound to occur. For a proper account of the mechanism of wear when this happens the reader must refer to the literature of this aspect of the subject, notably Ref. 36. Here it must suffice to mention the successive steps in the process of breakdown as revealed by the work of Bowden and Tabor and others—the progressive reduction in the thickness of the fluid oil film until only a monomolecular film remains (boundary lubrication); then support by the oxide film; then by films of phosphides, sulphides or metallic soaps which are formed by chemical combination with high pressure additives when the rising friction round the rubbing high spots raises the local temperature; finally metal-to-metal contact and an alternation of local welds and shears (stick-slip effect) often accompanied by the plucking of wear particles out of the weaker surface. During the initial stages of crest contact, provided complete seizure is avoided, plastic flow of the surface generally occurs, leading to the formation of the amorphous Bielby layer. Radio-isotope techniques have shown that there is generally some transfer of material from each surface to the other, making the structure of the outermost layers more complex still. The final run-in surfaces will therefore differ both geometrically and physically from their starting conditions, in ways which are vital to their ultimate performance and cannot be precisely simulated by any preparatory manufacturing processes. The author has noticed that this is so even in the case of optically worked bearing surfaces.

One important effect of the more closely spaced texture can be brought out by the familiar curve shown in Fig. 17.37, which relates the coefficient of friction with the dimensionless parameter ZN/P where Z is the viscosity of the lubricant, N the speed and P the load per unit projected area of the bearing. Mr. R. C. Spragg, working in the Taylor-Hobson Laboratory, has found that at least in some cases, if not all, the toe of the curve corresponds with the transition from fluid film to boundary layer lubrication. The effect can be seen quite clearly by displaying on the screen of a cathode ray oscillograph the behaviour of a small alternating voltage (50 millivolts from the 50 cycle mains is suitable) applied across the bearing. Of course the members must be insulated from each other everywhere else. Assuming constant load, at high speeds there will be no contact and a steady sine wave will be seen on the screen. As the speed is reduced the thickness of the oil film will become less until a speed is reached at which high spots begin to come into contact. Flashes from the sine wave towards the horizontal axis of the screen will then

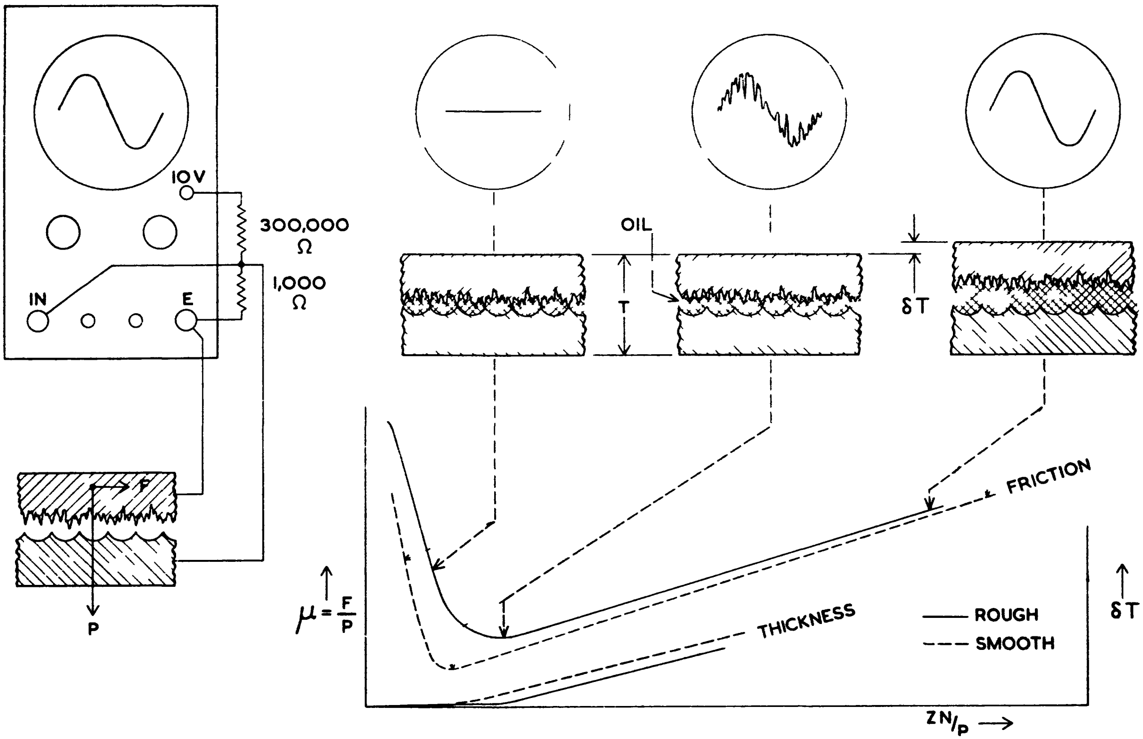


Fig. 17.37. Functional effect of primary texture in bearings

appear, and will increase in number as the speed is further reduced. Finally when the contact is continuous the spot will move in a straight line across the screen. Thus to the left of the toe there is continuous contact and rising friction with falling speed as the processes of boundary layer, chemical layer and metallic shear come successively into play. To the right of the toe the surfaces are held apart by a fluid film the thickness of which will tend to increase with increase of speed. The apparently increasing coefficient of friction in this region is perhaps accounted for by the increasing amount of work required to overcome the viscous drag of the oil film.

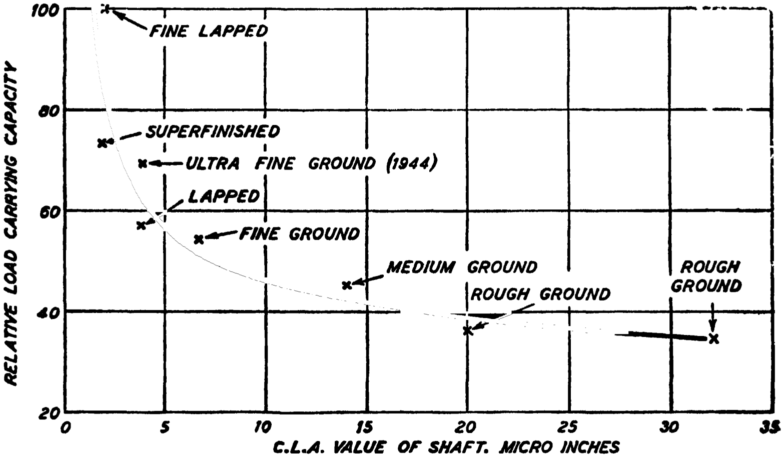


Fig. 17.38. Graph of W. E. R. Clay's results, showing relative load-carrying capacity of nitrided shafts finished in various ways, all running at 1,500 r.p.m. in diamond-turned lead-bronze bushes finished to 20μ in. C.L.A., with 0·001 in. diametral clearance and D.T.D. 109 Silvertown P.4 oil

If the primary texture is reduced in height, the toe of the curve will move towards the origin and become sharper, as shown dotted, because the average thickness of the fluid film can become less before high spots come into engagement. Improved finish, therefore, permits lower speeds or higher loads before the stick-slip region is entered.

It might be concluded that all sliding surfaces should start with as high a finish as possible. In practice this is not always the case, because often there are modifying considerations to be taken into account. In the classic case of aero-engine cylinders, for example, too fine a finish permits the build-up of an excessively thick oil film, and a definite roughness, produced by a series of carefully controlled processes, is essential to satisfactory performance (Ref. 34). Furthermore, if local seizure does occur, the result is likely to be more serious with very smooth than with rougher surfaces, partly because any weld particle that may be detached, or any dirt in the oil, has further to travel before it finds a gap in which it can lodge, and partly because protective oil will also have further to travel before it can reach the affected spot. Yet further, scratch marks having a favourable direction (lay), especially criss-cross patterns, can be helpful in distributing the oil over the surfaces. Again, if there are initial errors of form and bad alignment, very smooth surfaces may take longer to run-in than those that are not as smooth, apart from the greater risk of scuffing.

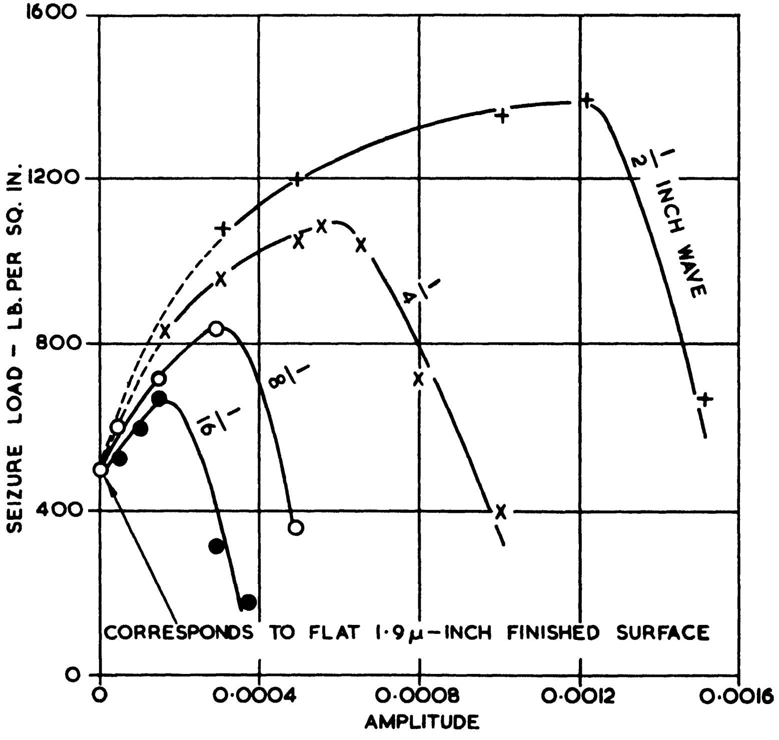
In the case of bearings, especially when a hardened shaft runs in a softer bush, there is clearer justification for high finish at least on the shaft. The results of some experiments carried out by W. E. R. Clay (Rolls Royce) are shown in Fig. 17.38. Roughly a ten-fold improvement in the finish of the shaft resulted in a three-fold increase in load carrying capacity.

The use of oils of very low viscosity enables machine tool spindles to run cool, but fine finishes are then required, clearances have to be reduced, and alignment correspondingly improved. Special attention has to be paid to filtration of the oil, but the result in performance and long life can be rewarding.

Secondary texture can be vitally important because of the part it plays in building up oil wedges. Some results for a 7 in. diameter flat thrust bearing obtained by Salama (Ref. 37) with a machine designed by Robinson and d'Souza at the Manchester College of Technology, are shown in Fig. 17.39. Waves of about $\frac{1}{2}$ in. circumferential pitch and 0·0013 in. height artificially lapped in one of the members increased the permissible load by a factor of about 3. In other words, they moved the toe of the $\mu/(ZN/P)$ curve towards the origin, affecting it in the same way as a refinement in primary texture. In the Taylor-Hobson Laboratory, it was found that in the region of very fine finishes, waves of a few micro-inches height could have at least as great an effect as the primary texture.

The texture of surfaces may be of consequence even when no rubbing occurs. The fatigue strength of highly stressed parts, for example, may be 10–30 per cent higher for lapped or polished than for rough ground surfaces (Ker-Wilson, Ref. 15).

Texture is also important in the case of interference fits. Particularly when one of the members is much harder than the other, the abrasion resulting from excessive roughness may seriously impair and even destroy the fit in the act of pressing the parts together. Even if such abrasion is avoided, for example, by shrink fitting, cavities between the surfaces left by the scratch marks may weaken the joint.



a

Fig. 17.39. Graphs obtained by Salama, showing how waviness on thrust bearing increased load carrying capacity by building up oil wedges. Note that for short wave-lengths (merging into roughness) there was no increase

The texture of finishing and also of pre-finishing stages may have to be controlled simply to secure the desired physical properties. For example, the surface heat and plastering action of a grinding process may seriously affect the crystal structure and temper of the outermost layers (up to at least 0·0002 in. deep) and set up undesired surface strains giving rise to surface cracks, and a cold abrasive finishing process (e.g. honing) may be justified more from the metallurgical point of view than from that of securing an initially smoother surface. The possibility that a process found to be good may be good because of its physical rather than its geometrical effects should always be borne in mind.

Texture of very fine spacing (almost too fine to be measured) may be important because of its effect on wettability and the adhesion of oil films to the surface.

Running-in ought probably to be regarded as a finishing process not necessarily reproducible in any other way, although favourable initial texture may greatly reduce the necessary time and increase the certainty of bringing the surfaces to their best condition.

It would be possible to cover many pages with an account of what is known in the various fields of application, for the literature of the subject is now extensive. References 4, 10, 15, 26, 28, 33, 35, 36–42 are but a few examples.

PART 2:

THE PREPARATION OF FINE SURFACES BY MACHINE METHODS

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Bristol Siddeley Engines Ltd.

Finish and Geometry. Fine surfaces can be taken to mean those having a greater degree of "smoothness" than is customarily produced by normal cutting methods. It is difficult in practice to divorce the control of surface finish from the control of geometric accuracy, except in cases where the quality of the finish is associated with purely decorative or process work.

Many problems involving consideration of fine surfaces are concerned with problems of wear and attrition of one or both of two surfaces which move on one another. In such cases geometric goodness and surface finish control are inseparable. It would, for instance, be useless to make a cylinder bore perfectly smooth if the geometric errors precluded effective sealing by the piston rings, and equally futile to produce a cylinder which was perfect geometrically, but so rough that the rings would wear out before they bedded in. Further, it may be even less profitable to expend time and energy producing a perfectly round and parallel cylinder with an extremely smooth finish, if that finish did not permit proper lubrication for reciprocating motion. Thus it may be said that surface finish and geometry are complementary to each other.

Broadly speaking, it can be said that the more accurately a tool does its work, the less rough is the surface produced, so that the general principles of producing work to very fine limits will apply equally to geometric accuracy and surface finish control.

The selection of the method by which a surface is to be produced will depend on a large number of variables ranging from the physical limitations imposed by the material and the duties to be imposed on the surface, to the commercial considerations of output.

The problems and responsibilities, therefore, facing an engineer charged with the production of suitable surfaces, will be found to come under the following six headings.

1. To determine and produce consistently the class of surface necessary for the functioning of the component, whether it be moving or stationary.
2. To select the method of finishing which will give the necessary dimensional control.
3. To produce the required surface mechanically in such a manner that it needs the least amount of hand fitting and the shortest running-in period.
4. To develop a surface which will give maximum life and minimum wear.
5. To select classes of surfaces and methods of producing them which do not create the risk of fatigue failure, or lower the physical properties of the material in highly stressed parts.
6. To select surface treatments or coatings necessary to protect the part from the effects of fretting or corrosion which may be harmful to its function or life.

In satisfying these conditions a number of methods of surface production will be considered, and they may now be studied in turn.

Diamond Turning and Boring. It is customary to find, where the application demands it, light alloys, bronzes and tin alloy bearing metals being turned or bored using diamond tools, with a geometric control of 0·0005 in. or below, and with surface roughness measurements of between 3μ in. and 5μ in. c.l.a.

Fine finishing by diamond tools is more or less confined to those materials which do not include hard or abrasive particles in their make-up, which would chip or damage the stone, and which cut cleanly with a definite chip or turning. Materials which come away in an abrasive powder rapidly erode the cutting edge, and those exhibiting this characteristic or components of forms which give interrupted cuts, make the use of diamond tools expensive and uncertain.

The machines employed for fine turning and boring must obviously be in perfect condition, with all ways and guides straight and true, and all bearings and spindles running in perfect truth with minimum clearance and no vibration.

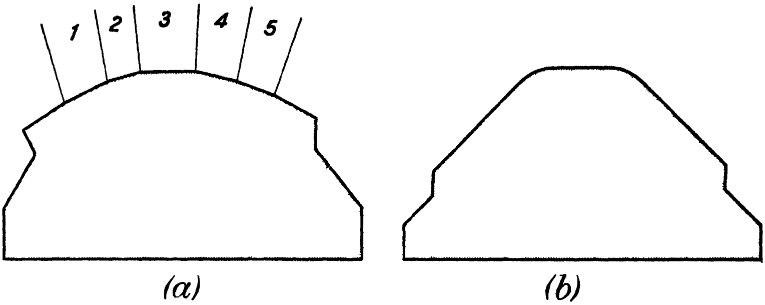

Fig. 17.40. (*a*) Multi-facet tool with facets approximately 0·020 in. wide. (*b*) Main facet of approximately 0·020 in. width blended radii into side facets

Diamond tool life, so often limited by hard spots in the material and by interrupted cuts, is potentially great, and where conditions are ideal, life between relaps equivalent to 700 miles of cut, are quite normal. The life of carbide tips is considerably shorter, but they are not so susceptible to damage from hard spots etc.

Cutting edge preparation is of fundamental importance, and it is essential that it be as near perfect as possible. Diamond tool manufacturers provide a service for re-lapping tools, which is a highly specialized process impracticable in the normal workshops. Tipped tools can be successfully lapped using diamond impregnated laps, there being no special knowledge necessary of such matters as cleavage planes, as in the case of diamonds.

Fig. 17.40*a* and *b* show greatly magnified the shapes of typical faceted diamond tools. Fig. 17.40*a* illustrates a multi-facet tool with facets 0·020 in. wide, not blended into each other, and Fig. 17.40*b* shows a main facet, again approximately 0·020 in. wide, blended into side facets.

Setting diamond tools is often carried out by experienced operators by observing the shape of the cut as the tool is gradually brought into the work, and from this observation they are able to judge the attitude of the cutting facet in relation to the work. The use of setting binoculars can greatly reduce the amount of trial and error in this process, and with less experienced operators, greatly aids setting.

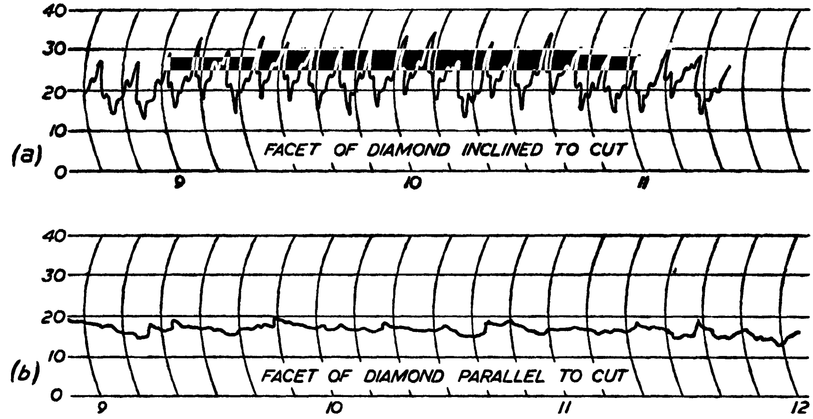

Fig. 17.41. Effect of setting of diamond on finish

Fig. 17.41*a* and *b* are graphical records obtained on a Talysurf instrument of surfaces produced by diamond turning and indicate very clearly the effect of setting on the character of the surface. Both graphs originally had a vertical magnification of 40,000 and a horizontal magnification of 200. The surface shown in Fig. 17.41*a* was produced with the facet of the diamond inclined to the cut and with a feed of 0·0044, and that in Fig. 17.41*b* with the diamond facet parallel to the cut, and a feed of 0·0088. Visually, the surface in Fig. 17.41*a* is brighter and more pleasing than that in Fig. 17.41*b*. This brightness is often mistakenly taken to indicate a finer finish than the less brilliant appearance of such surfaces as Fig. 17.41*b*.

A great deal has been written on cutting speeds and feeds for turning and boring, but when using diamond tools the best speed appears to be that at which the individual machine is free from vibration.

It has been shown that the limits of surface finish are primarily governed by the machine, and the setting of the tool, and it is good practice to determine the limitations of each machine for reference purposes.

Grinding. Grinding is the general way of finishing steel, but it requires a high degree of skill to repeat continuously a restricted grade of surface finish to fine geometrical tolerances.

The statement that surface finish and geometric control are complementary to one another is particularly evident in grinding, and small manufacturing tolerances almost invariably result in fine finishes.

In a works concerned with the production of hardened components with tolerances of between 0·0002 in. and 0·0010 in. finishes in the range 8 to 12 μ in. c.l.a. are commonly produced, and it has been noted that in producing finishes finer than that figure the danger of surface burning and cracking is greatly increased.

The machines employed for fine grinding must be in first class condition, with all ways and guides straight and true, and particular attention must be paid to the balancing of wheels.

Wheel surface preparation is of the utmost importance, and it is essential to keep the wheel as open as possible, to reduce the risk of burning and cracking to a minimum.

Adequate flow of chip and granule free coolant is equally important, as it has been found that the cleanliness of the coolant has a direct bearing on the quality of the surface produced.

The choice of wheel grit, speeds and coolants will vary with the material being cut and the finish demanded. Table 17.1 indicates the experience of one large works, but other combinations may well produce similar results.

TABLE 17.1. GRINDING DATA FOR VARIOUS FINISHES

Surface Finish μ in. c.l.a.	*Material*	*Wheel Grit*	*Work Speed ft./min.*	*Wheel Speed ft./min.*	*Traverse in./min.*	*Coolant*
5	Carburized Steel	60 M	250	5,500	22	Hocut "G"
8	Carburized Steel	60 M	190	5,500	22	Hocut "G"
16	Carburized Steel	60 M	180	5,500	22	Hocut "G"
45–50	Stainless Steel	60 M	152	7,500	22	Hocut "G"

Whilst grinding is a convenient and reasonably economic method of producing fine surfaces, it brings in its train a number of pitfalls. An inevitable result of grinding is the formation by the high temperature generated at the work to wheel contact line of an extremely thin layer of decarburized material, which has a considerable effect on the initial efficiency of a surface as a bearing, and has to be removed in many cases before really satisfactory bearing conditions are attained.

A further effect of high temperature is burning of the surface and the formation of grinding cracks, which are large enough to affect the fatigue strength of the component, but too small to be found except by specialized methods of crack detection.

Lobing or chatter is also evident on ground cylindrical components, particularly on those which have been centreless ground. These lobes are always odd in number, and are not always discernible by two point measurement, but may be found by three point methods, by blue marking checks, or with special measuring machines such as the Taylor Hobson "Talyrond".

Honing. Most of the disadvantages noted in connection with grinding may either be removed from a surface by honing, or avoided altogether by a suitable combination of the two processes.

Properly designed hones, with carefully selected honing strips are capable of reproducing a desired finish over an almost illimitable number of components, with a dimensional and geometrical control of considerable accuracy.

The decarbonized zone produced by grinding, sometimes called "fuzz", may be removed quickly without producing some other undesirable condition, leaving the surface in an excellent state for bearing purposes.

The Talysurf graphs shown in Fig. 17.42*a* and *b* are produced from the surface of a case hardened steel pin 1 in. diameter, successively ground and honed to 10 μ in. c.l.a. and $\frac{1}{2}$–1 μ in. c.l.a. respectively. A piece to piece variation in diameter after honing of not more than 0·0002 in. is experienced with ovalities not exceeding 0·00002 in.

The design of hone tool used to produce components of this order of accuracy should be such that the honing strip or stone position is under definite control, and be sufficiently strong to avoid distortion under cutting loads. It has been found good practice to rotate the component where this is possible rather than the hone tool. The drive between the machine and the component or hone, whichever is moving, should be such that there is no constraint which may cause geometric errors.

In producing the surface shown in Fig. 17.42, hones with speeds of 200 r.p.m. and 67 strokes per minute were used with copious supplies of lard oil and paraffin as a coolant.

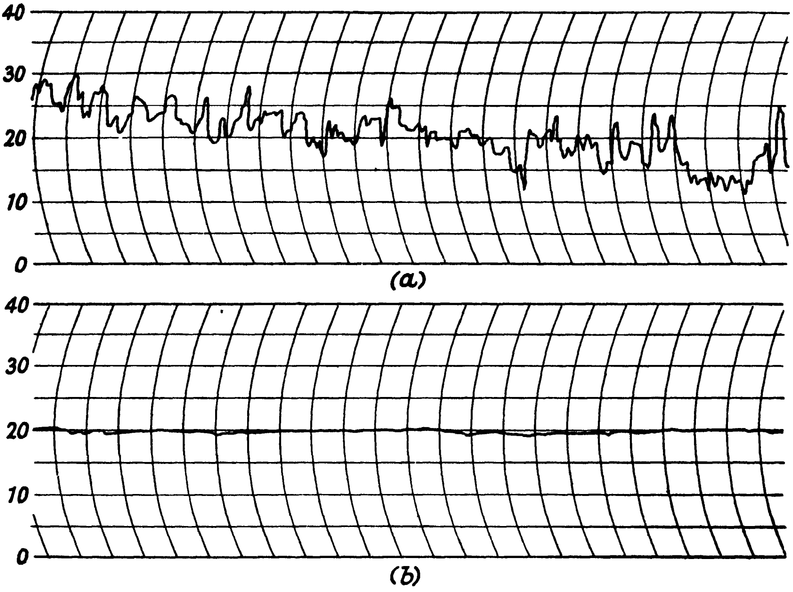

Fig. 17.42

(*a*) Groundfinish 10 μ in. c.l.a. 60 M grit wheel. Work speed 50 ft./min. Wheel speed 5500 ft./min. Graph × 20,000 vertical magnification, × 200 horizontal magnification.

(*b*) Honed surface 1 μ in. c.l.a. Carborundum C.700 grit stones. 200 rev./min., 67 strokes/min. Graph × 40,000 vertical magnification, × 200 horizontal magnification

As in grinding, it is important that the coolant be free from foreign matter, and filtering or centrifuging are common practice.

Honing should not only be associated with the production of surfaces of low surface roughness values, but considered as a valuable contribution to the production of geometrically accurate internal and external cylinders, without the disadvantages associated with the high temperatures generated in grinding.

Other Methods. The means of preparing surfaces described earlier in this chapter are basically machining methods, but valuable contributions to the science of surface production are made by other means.

Shot blasting under careful control produces a state of stress in the surface, which under some circumstances may be directed to reducing fatigue failure of the component.

For large quantities of small articles, particularly where the requirements are not exacting, parts to be blasted are placed in a rotating drum and the shot projected into it by air blast. Larger articles needing more precise control are treated separately, the shot being impelled by air blast or from the rim of a high speed wheel.

It is important that the shot used is not broken, otherwise sharp bottomed indentations may be formed which will have the reverse effect to that aimed at.

Polishing with mops and brushes impregnated with abrasive compounds may be usefully employed in a number of cases to improve appearance, and to smooth out stress concentrations. It does, unfortunately, involve considerable local surface heating, and heat treatment at low temperatures to remove the effect of such heating is sometimes necessary with some steels.

The speeds of brushes etc. and the abrasives used will vary considerably with materials and shape of the component being finished.

Surfaces of from 3–5 μ in. c.l.a. without intermittent deep scratches are obtained with felt mops dressed with 120 grit emery and Albo grease followed by brushing with fibre brushes at 5,850 ft./min. on a steel component of complicated shape.

Application of Fine Surfaces. A great deal has been written on the application of fine surfaces, and the following examples will indicate the range of effect small variations in surface condition may have on the performance of the finished part.

The preparation of spindle bearings of certain types of diamond turning and boring machines show an advantage of precision machined bearing surface preparation over hand preparation. Originally the machine spindle was ground to a good finish, and the adjustable bronze bearings were bedded in by hand scraping. In service it was found that if the bearings were slack enough to run freely, a poor finish of the job being bored resulted, and when they were tight enough to produce a good finish, the spindle tended to fire up. As the operating loads were small, the application appeared to be one calling for fine finish, and geometric accuracy to permit small clearances; in fact 0·0003 in. clearance on a 2·25 in. diameter shaft was aimed at.

Plain bronze bushes were fitted in well seasoned cast housings, and bored in position, the final cuts being made with a diamond tool.

Fig. 17.43*a* indicates the character of the bearing surface when hand scraped, and *b* the same surface in service. *c* indicates the diamond bored bearing, which in its general form is preferable to the hand scraped surface after running in.

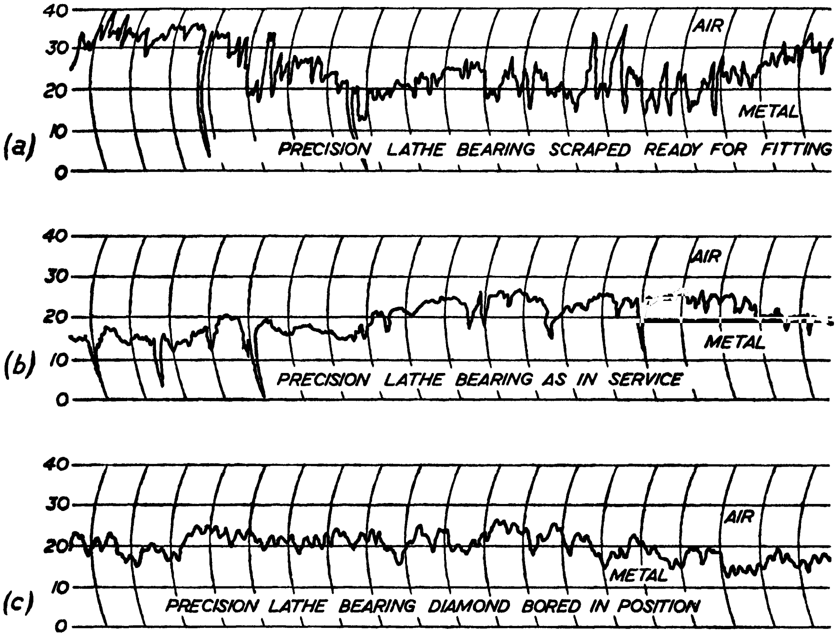

Fig. 17.43. Hand-scraped and diamond-bored finishes

The bearing bore was round and parallel within 0·0001 in. the final 0·0002 in. diamond cut being taken at 300 r.p.m., with a feed of 0·0015 in. The spindle was hardened and ground high grade mild steel, finally hand lapped and polished to almost a zero surface finish reading with errors of size and shape in the order of 0·00005 in. The assembly was subjected to slow "running in" up to its speed of 1500 r.p.m. over several days, and after two years production boring was still able to produce work of extremely high quality.

A second example concerns the measures taken to prevent green seizures of a connecting rod bush on the wrist pin of a radial engine. The motion of this bearing is one of semi-rotation, and it is pressure lubricated. The bronze bush was originally diamond bored to a finish of 6–8 μ in. c.l.a. and the pin ground to around 8 μ in. c.l.a.

The first line of attack was to improve the surface of the bush, and this was done by roller burnishing. This operation consists of lining the bore of the bush, which is 1·128 in. + 0·0005 in. diameter with a crowded set of eighteen round-ended rollers 4 mm. diameter, and passing through the centre, copiously lubricated with filtered castor oil, a rotating bar with a slow taper of 0·0015 in. in 7 in. When fully engaged the size of the large end of the bar is such that an interference of 0·001 in. to 0·0016 in. is imparted in the bush, and the result of this operation is a surface varying from 1½–3 in μ c.l.a.

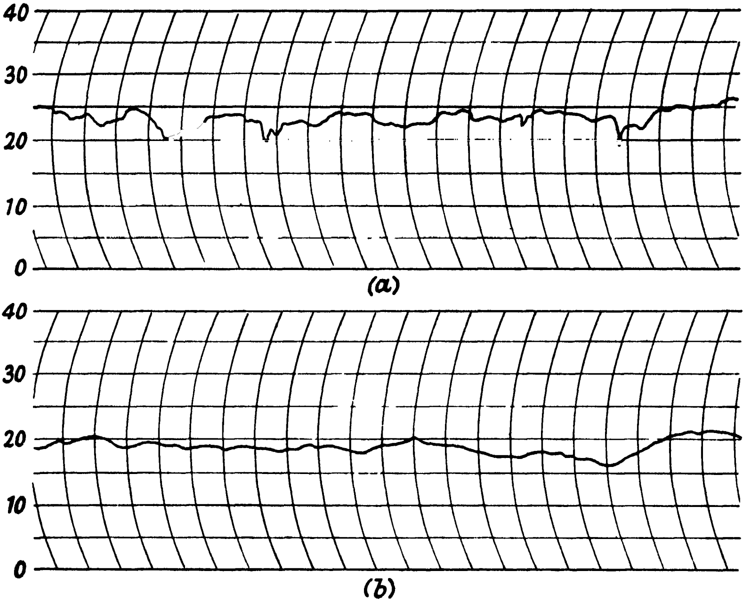

Fig. 17.44

(*a*) Diamond-bored finish 2–2½ μ in. Graph × 40,000 vertical magnification, × 200 horizontal magnification

(*b*) Roller burnished finish 1–1½ μ in. c.l.a. Graph × 40,000 vertical magnification, × 200 horizontal magnification

Fig. 17.44 indicates the character of the surface before and after burnishing, the final surface being very smooth.

To complete the cure the pin was honed from the ground finish of 8–10 μ in. c.l.a. to a surface of less than 1μ in. c.l.a., using a hone as described earlier in the chapter. The resulting surface is shown in Fig. 17.42 together with the grinding from which it is produced.

Unlike the machine bearing, this one cannot be subjected to long and carefully controlled running in, but has to take up its duties on starting the engine to which it is fitted, and the surface production changes have resulted in elimination of green seizures of the bearing.

It has been said that all fatigue failures of components result from tensile failures at the surface, and so any action taken to produce a surface which reduces the possibility of such failure is of value. The development in a surface of some degree of surface compression, and the smoothing out of stress concentrating changes in section, notches and scratches, are two means of approach.

Examination of fatigue failures of the gudgeon pins of an aero-engine showed each of them to originate from the bore surface. The pins are 5 in. long and 1·5 in. outside diameter, the bore being tapered from a maximum at both ends to a minimum in the centre for stiffness.

The outside diameter was ground and honed to provide good geometric form and finish, and the bore ground to a commercial finish of 40–60 μ in. c.l.a.

As a result of examination of the fractures two steps were taken. Firstly to smooth out the surface of the bore, a maximum surface roughness of 10 μ in. c.l.a. was agreed upon.

This was commercially acceptable, and offered a reasonable improvement in surface condition. Provision of surface compressive stress by nitriding the component all over was decided upon, which meant that complete machining to finished size was possible before treatment, and only a light hone on the outside diameter to remove the bloom of nitriding was needed after treatment. This dual approach on one component was successful, and further failures were prevented.

Thus it may be stated that the method of producing and the quality of a surface have considerable bearing on the ability of the surface to perform its allotted function.

For Bibliography see end of book.

CHAPTER XVIII

JIGS AND FIXTURES

By HENRY FOWLER

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IN large engineering works jigs and fixtures are essential when large numbers of components are to be machined accurately to the same dimensions. A *jig* may be described as a plate, metal box or structure on to or into which components are clamped in identical positions one after the other. In the structure, suitable holes are machined to match in size and position the holes shown on the machine drawing of the component. When the component is presented to the machine, the holes in the jig thus act as a guide for the cutting tools employed and ensure that on completion of the machining, the relative positions and sizes of all the holes in the components processed on the machine are exactly the same.

A *fixture* may be described as a structure to hold and locate a component or workpiece in a definite position. Unlike a jig, a fixture does not positively locate the cutting tools, but is usually provided with setting pieces to ensure the correct relationship between the location points and the cutter. A fixture is usually bolted to the machine table of a milling or boring machine; with a jig, this is often unnecessary.

Simplicity, but perfection of form in jigs or fixtures will contribute largely to their efficient performance when in operation, therefore, the jig and tool draughtsman, by working to narrow and rigid limits in design, will ensure that the equipment provided will guarantee accuracy and interchangeability of component parts.

Principles of Design. The following principles relative to the design of efficient jigs and fixtures should be observed. The equipment should be: (1) as robust as is necessary for the operation, especially when milling, boring or turning; (2) as light as possible for drilling operations, particularly where the jig is to be constantly handled; (3) as simple as possible in construction, consistent with correct performance; (4) as quick-locating as possible, incorporating cam-action or air-operated clamps where feasible; (5) as clean as possible in design so as to avoid the accumulation of swarf around important location points; (6) made foolproof.

ROBUSTNESS. Unlike a jig, which may frequently have to be moved, a milling or boring fixture is usually bolted to a machine table or to the spindle nose or faceplate of a lathe, and is not removed until completion of all the components that require machining. Its size and weight, therefore, unless there are limits imposed by the machine-tool to which the fixture is bolted, need not be so restricted as with a jig and, as a result, we are able to design the robust type of equipment so essential in a milling or boring fixture which has to absorb vibration and shock loading when cutting tools come into operation on the component.

LIGHTNESS. The construction of a drilling jig does not require the same degree of robustness as a milling fixture, since the cutting tools invariably contact machined faces, and the initial load transmitted to the jig body is not as severe. With many drilling jigs in use on light pillar drills it is usual to slide the jig into position under the drill by hand. This point should have due consideration when designing.

SIMPLICITY. Simplicity of design not only reduces the work for pattern- and core-maker, or others concerned in the making of the jig or fixture, but also makes for greater reliability when the equipment is subjected to continued wear and tear or mishandling.

SPEED IN LOCATION. Too much emphasis cannot be given to making provision for quick and easy locations, that is, arranging that the component can be easily loaded into the jig or fixture. The operator should be able to drop or slide the component into position, without having to "wangle it in", and adequate clearances should be allowed between the workpiece and the surrounding walls of the jig or fixture. All clamps and adjustments should be on the operator's side of the structure and, where spanners are used to fasten clamps, the same size of nut should be used at all clamping spots. Quick-acting clamps, particularly cam-action clamps should be considered, especially where light machining loads are involved, since they often enable loading time to be comparable with machining time.

Air clamping is an efficient method of quick clamping and eliminates fatigue in the operator, but it is more applicable where constant production of certain types of components are concerned than where intermittent production of small batches is required.

CLEAN DESIGN. Jig and tool draughtsmen should fully appreciate the importance of clean design. Location points should be clearly defined and so designed that they do not hold swarf.

Accumulation of swarf around clamps is a very bad feature. If the jig or fixture is a box-type structure, adequate apertures should be incorporated to permit the removal of swarf and the drainage of coolant. In this connection it is well to consider the area of the jig or fixture in relation to the machine table, because it is easy at the design stage to incorporate suitable drainage channels to allow coolant to drain to the machine table troughs. A good design will obviate the unsightly, and often dangerous, splash guards which operators erect to prevent coolant from reaching the machine shop floor.

MAKING FOOLPROOF. In simple terms, foolproofing means the provision of adequate devices to make it impossible for an operator to insert a component into a jig or fixture in any position other than the correct one. There are many ways of providing suitable obstructions, the choice always being governed by the particular component for which the jig or fixture is being designed, although, due to the symmetrical shape of some components, it may not always be possible to provide a "fouling piece". In such, a suitably inscribed brass plate may be attached giving requisite instructions to avoid incorrect positioning of the component.

Milling Fixtures. The foregoing fundamental principles can now be considered in relation to the design of milling fixtures. A milling fixture is usually required for the first of a sequence of operations upon a component, and the operation will, therefore, be expected to provide the faces and locations to which subsequent operations must be related. It should, therefore, incorporate all the features required to "balance" or "equalize" the workpiece, that is, to relate the various operations to the workpiece in the best possible way.

If we consider the component to be a casting having flat faces that require milling, the first step in the design is the choice of three points of support which will carry the casting without rocking, and which will determine the position of the supporting jacks in the fixture.

JACKS. Support jacks of two different types may be provided, fixed, as shown in Fig. 18.1*a*, and fixed adjustable, as shown in Fig. 18.1*b*. The fixed type is used where there is a reliable degree of constancy in the shape of the casting and adjustment is only occasionally

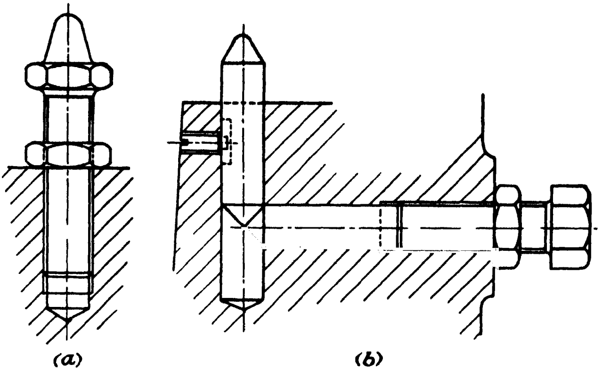


Fig. 18.1

necessary. Fixed adjustable jacks are used where constant balancing of the component is necessary, and, in order to make this adjustment convenient to the operator, the control of the adjustment may be made at right angles to the support jack, and operated from outside the body of the fixture. Fig. 18.2 illustrates an adjustable Vee-type jack which may be applied when a component requires supporting

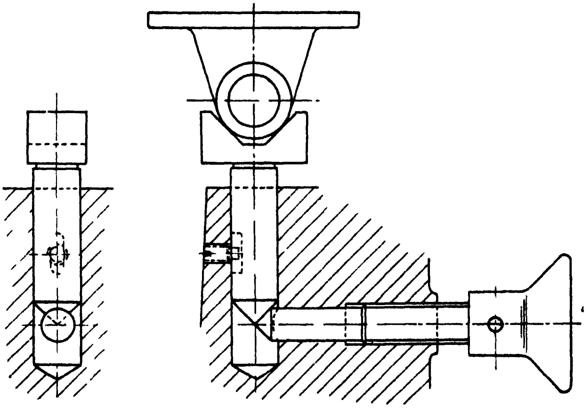


Fig. 18.2

on a round section of its profile. When it is necessary to provide a four-point support for the seating of a component the provision of a compensating device as shown in Fig. 18.3, used with two of the jacks previously mentioned, will enable the workpiece to be accommodated in this manner.

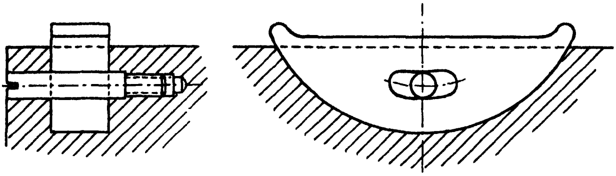


Fig. 18.3

Profile Plates. Having seated the component, the lateral equalizing of the casting should now be considered. This is done with plates shaped and applied to the important profiles of the component, thus ensuring the correct relationship between the important faces of the component and the first face to be machined. It is advisable that these profile plates should be presented to the component in such a manner that sighting can be made easily and accurately. The shape of the workpiece being considered determines the shape of the profile plates, and a simple type of profile plate for sighting two bosses on a component is shown in Fig. 18.4.

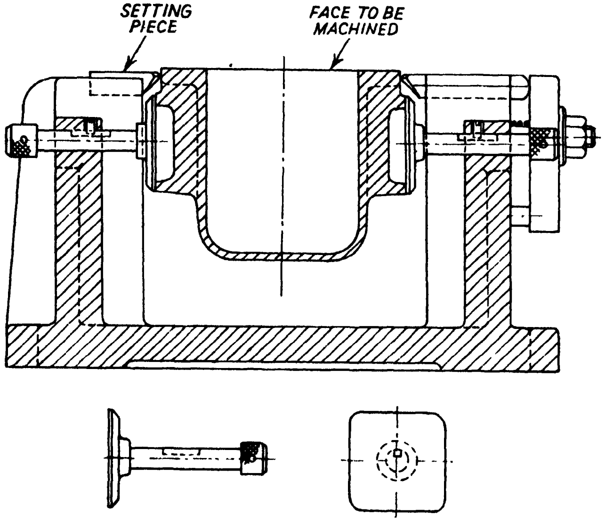


Fig. 18.4

It will be observed that by presenting the profile plate direct on to the boss facing, a true sight or "feel" may be obtained.

Fig. 18.5 indicates in how many ways and directions the tool/workpiece relationship may be provided for in a single fixture.

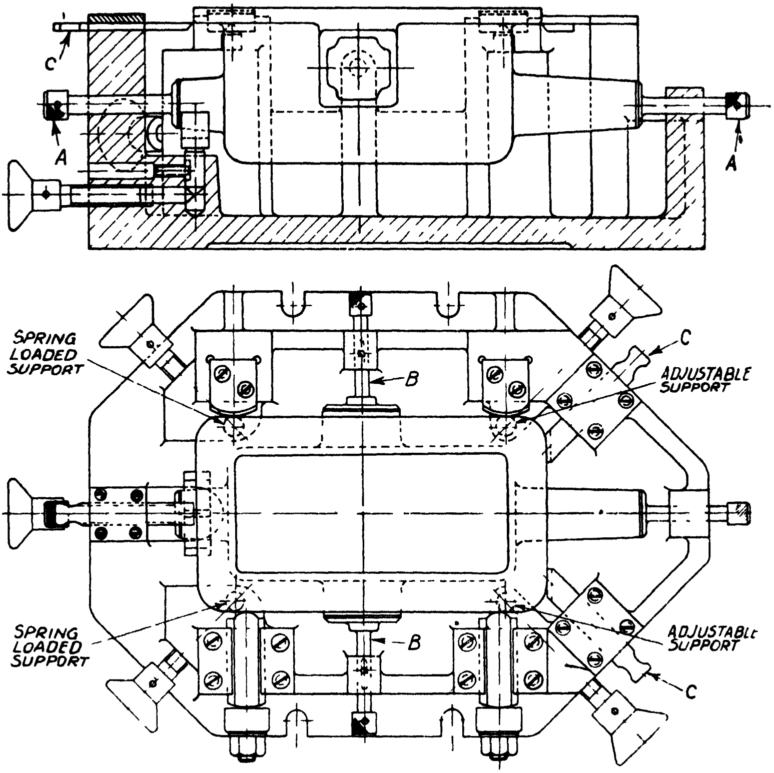


Fig. 18.5

Profile plates *A* are positioned at the extremities of the two long bosses, while profile plates *B* take care of the two boss faces in the opposite plane. Sighting plates *C* ensure that the thickness of the flange is maintained relative to the machined face.

CLAMPS. Clamping the component into the fixture is most important and a review of various methods that may be adopted is advisable at this stage.

In general, cam clamps are not advised for use with milling fixtures, since they are unreliable where shock loading by the cutter has to be considered. Fig. 18.6 shows examples of clamps in general use with both jigs and fixtures, *a* showing a fixed clamp heel and *b* a heel with adjustment.

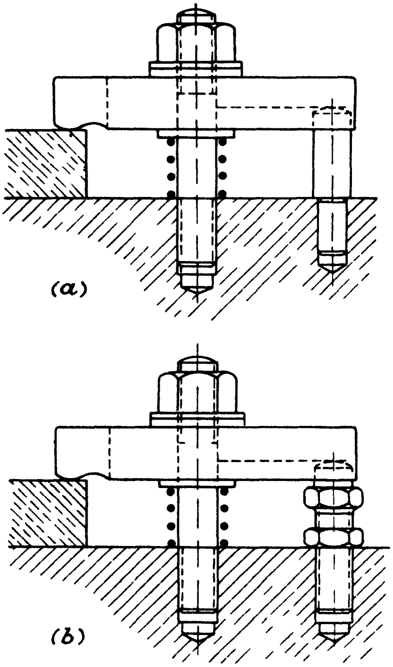


Fig. 18.6

To compensate for a clamping load on two points of a casting, a swivel may be incorporated into the clamp body. Fig 18.7 shows a Vee-type swivel clamp which is easily adaptable for application on light and hollow castings when, in conjunction with the Vee-jack support indicated by Fig. 18.2, a clamping effort is distributed around four points of a component, thereby reducing the possibilities of distortion.

It is often practicable to provide a type of cam-action clamp where light clamping loads are sufficient to retain a workpiece in a fixed position. Figs. 18.8 and 18.9 are typical examples, and have proved reliable provided there is little or no variation in the thickness or diameter of the component. The amount of eccentricity of the cam should be carefully calculated to ensure that the cam rise is not too rapid and so that sufficient mechanical advantage may be obtained.

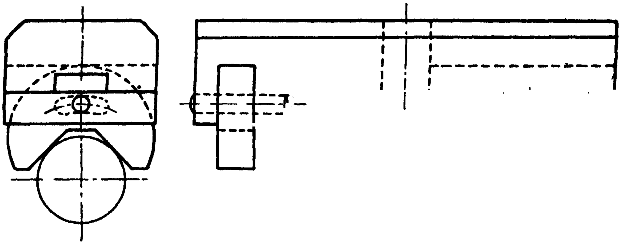


Fig. 18.7

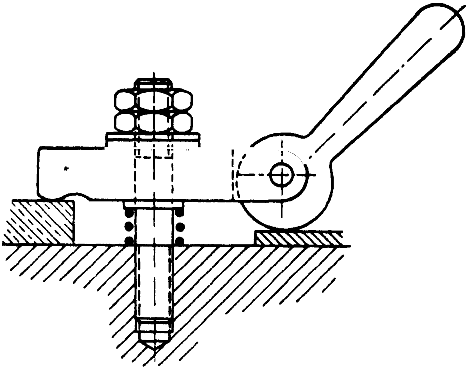
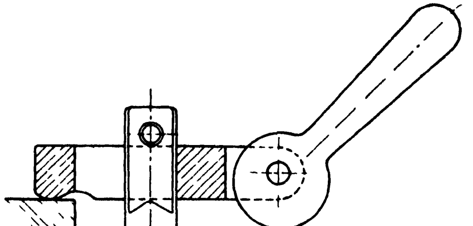


Fig. 18.8



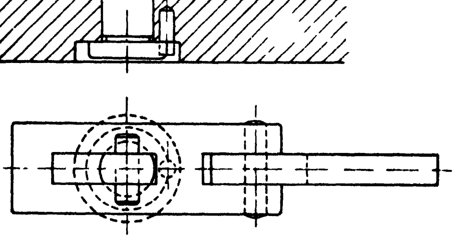


Fig. 18.9

The two-way clamping device (Fig. 18.10), in which effort is exerted in two directions by the action of one screw, is another method of retaining light components.

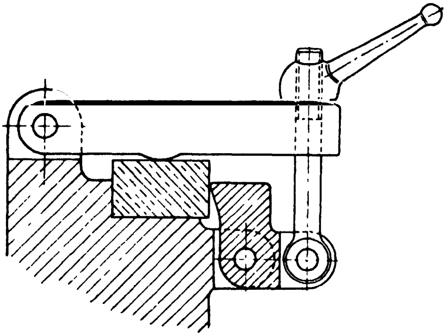


Fig. 18.10

Multi-point clamping is often an advantage when large quantities of small components are being considered. Fig. 18.11 indicates a fixture designed for milling two flats on a round bar, and it will be observed that use is made of each component to provide a means of holding its neighbour. The workpieces are located in hardened and ground vee blocks *A* which are free to slide in the body of the fixture and retained by "keep plates" *B*. A sliding extension block *C* transfers effort from clamp *D* to the components, all being secured

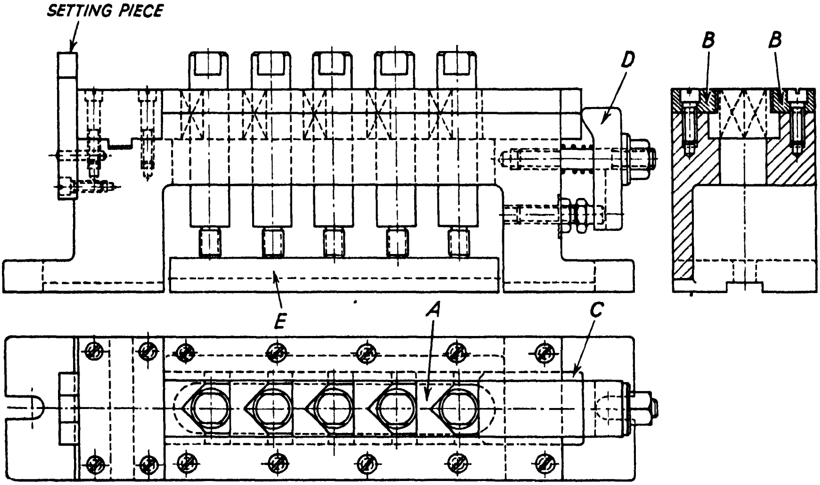


Fig. 18.11

by the one clamping medium. The Vee blocks are designed to accommodate various diameters within certain limits. To accommodate varying lengths, a loose support block *E* is provided; this may be removed, and another suitable for the workpiece in progress, substituted.

There are many occasions when the type of clamp previously mentioned cannot be applied, particularly where the flange of a component requires clamping and the effort is necessary close to the face of the milling cutter. Fig 18.12 shows a very effective clamping device which overcomes the difficulty. The sliding portion of the clamp *A* is accommodated in a machined slot in the body of the fixture *B* which is retained by "keep plates" *C*. The effort is applied at right angles to the sliding portion by an ordinary type of clamp *D*. It also provides a useful method of compensating the clamping of a workpiece to enable equal effort to be applied simultaneously at two points *E*.

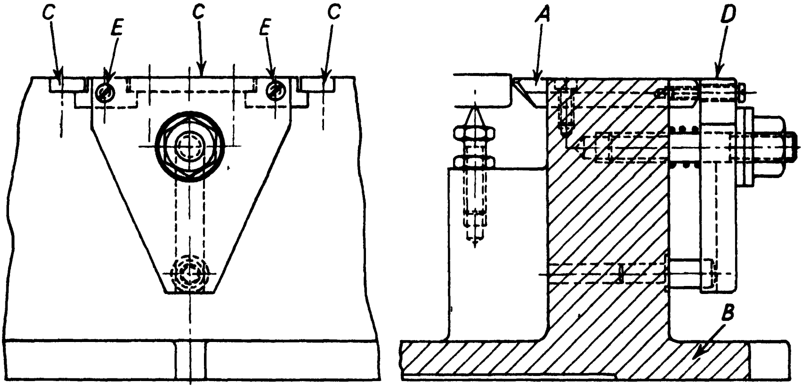


Fig. 18.12

A point to be considered when making arrangements for clamping the workpiece to the fixture is the position of the clamp stud in relation to the point of application and the clamp heel. If the practice of maintaining the same distance between the clamp stud and these two points is adhered to, an effective grip will always be assured.

When allowing for out-of-squareness between the nut and the clamp, it is not good practice to machine a spherical facing on one and a seating in the other, on the assumption that by doing so it will correct misalignment. It is far better to provide a complete washer of the type shown in Fig. 18.13.

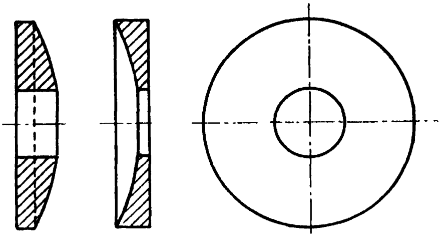


Fig. 18.13

The resistances or "stops" *A* in Fig. 18.14, against which the component is forced by the clamps, should be sturdily constructed and well backed up by the body of the fixture. Consideration should be given to their position relative to the profile of the work, as it is an advantage to have them well spaced. The simple example shown

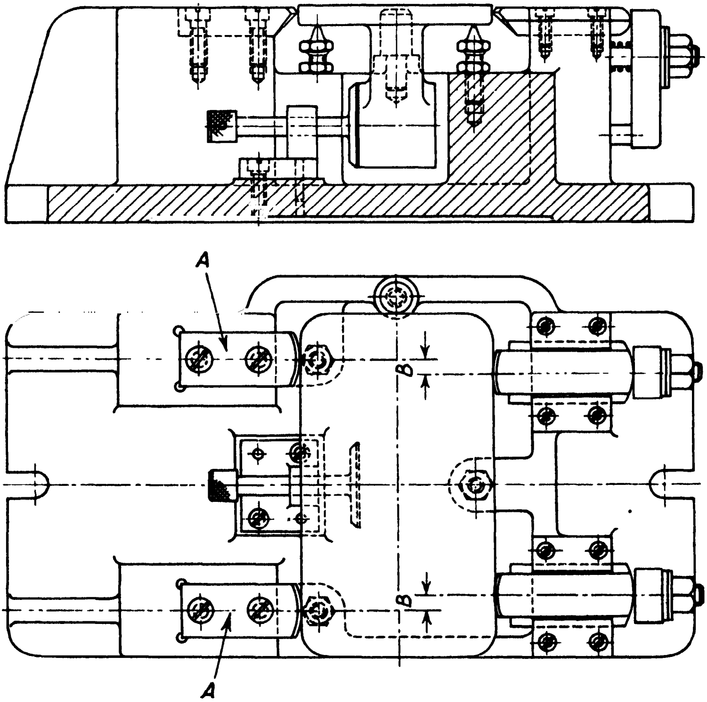


Fig. 18.14

in Fig. 18.14, illustrates the above points. It will also be noted that the clamping points *B* are inside the width of the resistances, this feature being necessary to ensure that the component is firmly fixed and that it is not being displaced when the clamps are tightened individually.

We may find that three jacks are not adequate to support the component over the full area of machining. When this occurs extra spring-loaded jacks are usually provided. Fig. 18.15 shows a simple type operated from outside the fixture. The method of operation is to depress the plungers *A* and lock them in their lowest position before assembling the work into the fixture. When the work is seated on the three, main, locating jacks and firmly clamped, the spring-loaded plungers are released to come into contact with the work, afterwards being locked into position.

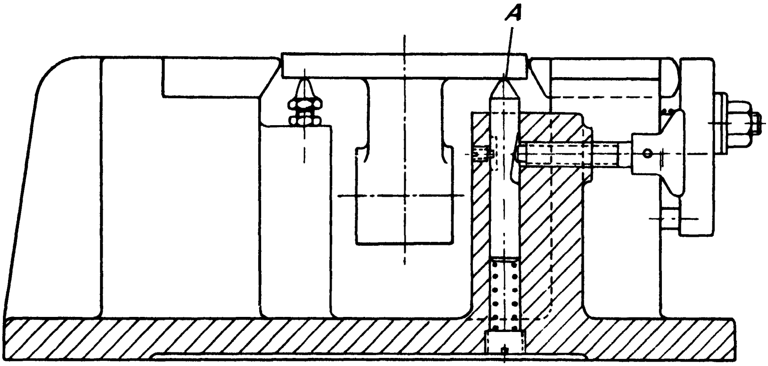


Fig. 18.15

Setting Pieces. The design and position of the setting piece may now be considered. The most common type of setting piece in use on face milling fixtures is rectangular, or square, in shape, made from a case-hardened material, hardened and ground on both faces, with socket-head screws for retaining the setting piece to the body of the fixture. From the position of the profile or sighting plates is determined the relative height of the setting piece, allowance being made for a feeler gauge between the setting piece and the cutter. A convenient size of feeler gauge is 0·060 in. which permits a sufficient gap to be maintained, and allows for minor adjustments without danger or damage to the cutter.

General Construction. The shape of the fixture body has to some extent been determined by the design considerations we have followed so far, but we should now consider the details to finish the general construction.

A simple structure may be fabricated, but if we have a complicated one, trouble is often experienced in having the fabrication annealed. Although this, of course, relieves the stresses in the structure and permits a high degree of accuracy during manufacture, it is generally agreed that a cast iron body gives better wearing qualities and is capable of absorbing rough treatment without distortion.

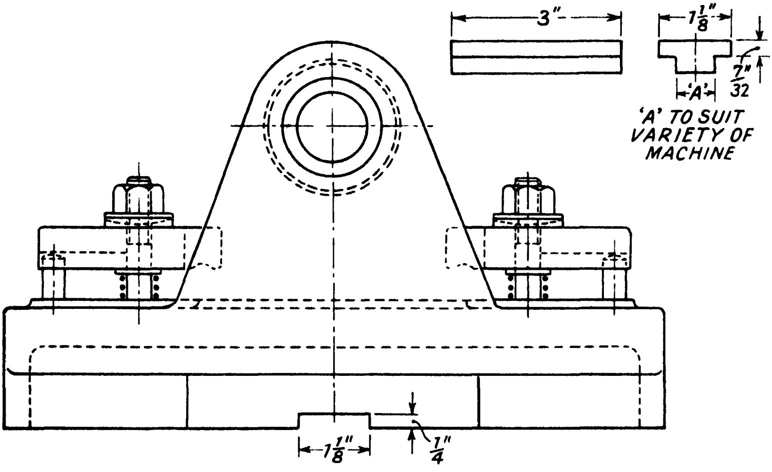


Fig. 18.16

The height of the structure should be considered at this juncture. It will be clear that the closer the work is to the table, the less likely it is that vibration will be experienced.

Tenon slots for the location of the fixture on the machine table are necessary to ensure that the work locations are square to the axis of the cutter spindle. To enable fixtures to be accommodated on various makes of machines, which may have different. widths of bolt slots, it is usual to mill in the fixture a slot that will cater for a universal type of tenon. A typical one is shown in detail in Fig. 18.16.

Provision for suitable lifting hooks is necessary, particularly when designing heavy fixtures, and two, three or four tapped holes in predetermined positions to accommodate suitable eye bolts, may greatly facilitate the handling of a heavy piece of equipment. To ensure that a jig or fixture will be perfectly seated when in operation, it is usual to relieve the base, thus accommodating any local irregularities that may exist on a machine table. The toolmaker will also find this relief of great benefit when scraping the base during manufacture.

Up to now we have been concerned with the first milling operation on a component. This is usually followed by the drilling and, often, reaming of holes in a face that has already been milled. However, to keep operations of a similar character together, we will first consider briefly the next milling operation. In this, use is made of the drilled or reamed holes for location of the component, and, generally, the two holes having the greatest distance between centres are chosen for this purpose. When the location is taken from two such holes a full-diameter pin is used for one position and a diamond-shape pin for the other; thus allowing for slight errors in the spacing of the holes and making loading and unloading much easier. The angular position of the diamond pin relative to the other is important (*see* Fig. 18.17) otherwise faulty location will be obtained.

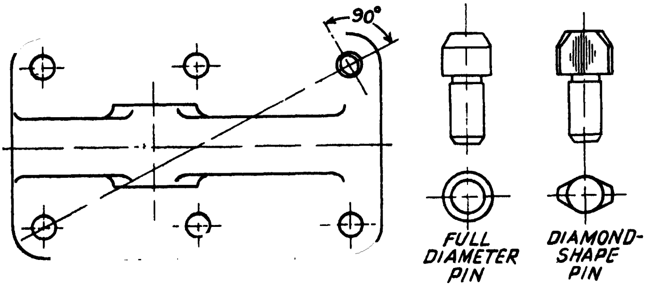


Fig. 18.17

It is often an advantage to consider plunge cutting when designing certain types of milling fixture, this application having certain favourable features as opposed to traversing the work over the periphery of the milling cutter. First, the cutter, working on the centre-line of the workpiece, eliminates the necessity of having to consider the direction of rotation of the milling cutter with respect to the traverse of the machine table, and secondly, it will be found that the time taken to complete the milling operation by this method will be less. Fig. 18.18 illustrates plunge cutting on a simple component, two cutters being used to face both sides of the boss simultaneously.

By using a 0·060 in. feeler on each side of the setting piece, the

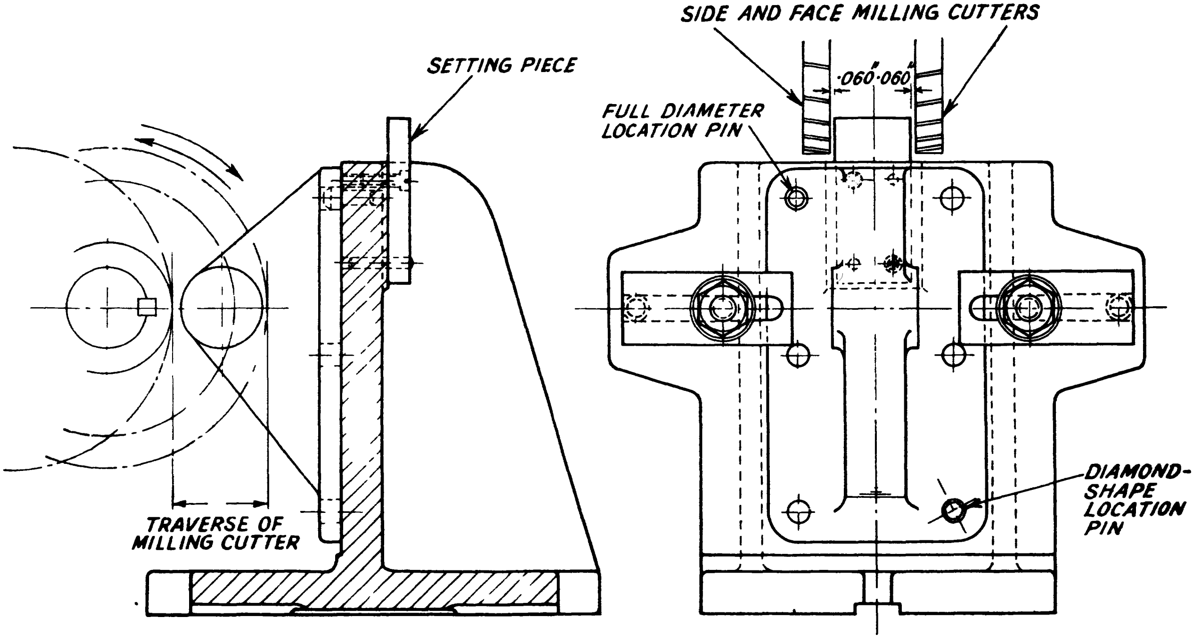

SETTING PIECE
TRAVERSE OF MILLING CUTTER
SIDE AND FACE MILLING CUTTERS
·060" ·060"
FULL DIAMETER LOCATION PIN
DIAMOND-SHAPE LOCATION PIN

Fig. 18.18

milling cutters are positioned so that the boss may be milled to the requisite width, the machine table then being raised to bring the cutters into their operational position.

Drilling Jigs. Having considered some of the fundamental principles of milling fixtures, we will now consider drilling jigs. Usually, drilling operations follow preliminary operations such as milling, turning or boring, and in consequence there is a machined surface from which a component may be positioned. The size of a jig depends on the dimensions of the work under consideration, and, as was pointed out earlier, minimum weight should be aimed at in order to evolve the most convenient form.

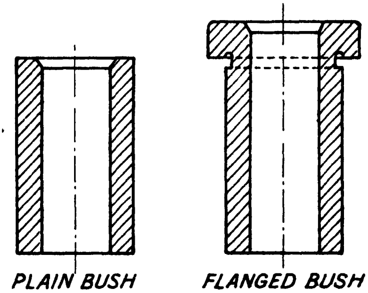


Fig. 18.19

DRILL BUSHES. Before beginning the design we should acquaint ourselves with certain details that will increase the efficiency of our equipment, the first being the drill bushes (Fig. 18.19).

Drill bushes should be of sufficient length to pilot a drill or reamer adequately. There is no set constant for determining this length, but a common rule is that twice the diameter equals the length of the bush for drill sizes over half an inch, and if this is followed effective pilotage of the tools should be assured. Flanged bushes may be used to obtain the required lengths without increasing the thickness of the supporting drill plates.

Wall thickness of the type of bush illustrated in Fig. 18.19 may generally be determined by adopting the following standards $\frac{3}{32}$ in. thick up to $\frac{1}{4}$ in. bore, $\frac{1}{8}$ in. thick up to $\frac{1}{2}$ in., $\frac{5}{32}$ in. thick up to $\frac{5}{8}$ in., $\frac{3}{16}$ in. thick up to 1 in., $\frac{7}{32}$ in. thick up to $1\frac{1}{4}$ in. and $\frac{1}{4}$ in. thick for larger bores, but more concise dimensions are given in B.S. 1098 : 1953. It is usual to make these bushes a press fit in the jig plate, but occasionally, for accurate location purposes, it is necessary to make the bush a "push fit" and, to cater for this departure from accepted practice, the bush head or flange is drilled and counter-bored for retaining screws. When a high degree of accuracy and finish of the hole is necessary, it is usual to drill the hole undersize and finish with a reamer, the drill plate being then provided with a series of liner bushes to accommodate the use of slip bushes, these having bores to suit the reduced size of drill and finishing reamer. A simple type of liner and slip bush is shown in Fig. 18.20.

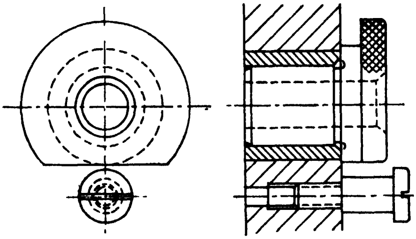
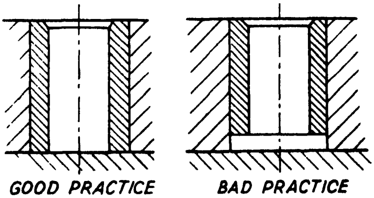


Fig. 18.20

It will be noted that the flange on the underside of the knurled head of the slip bush is greater than the outside diameter of the liner bush, this difference in diameters preventing the slip bush from pushing the liner bush through the drill plate. The knurled head,, being greater in diameter than the flange, provides a means of ejection from the liner bush.

The knurled head of the slip bush is flatted to enable the bush to pass the stop screw and, when positioned in the drill plate, is prevented by the screw from lifting and turning. A robust size of screw is recommended for this purpose, due to the heavy pressure exerted by swarf on the walls of the bush.



·Fig. 18.21

Whenever possible, it is advisable to have a drill bush flush with the face of the component, thus preventing an accumulation of swarf that would persist if a gap existed. Drill breakages and ejection of the bushes are often the result of failure to observe this very important feature. Fig. 18.21 indicates good and bad practice of mounting bushes.

DRILL PLATES. When drill plates are secured to a jig body (*see* Fig. 18.22) it is advisable to provide a gap, sufficient to allow swarf to escape between the work and the plate, in this case the use of a flanged bush is advocated. A fault, found very often in jig design, is that the area on the jig body allotted for the seating of the drill plate is too small, and a good general practice is to make the length of the seating equal to the overhang, as shown.

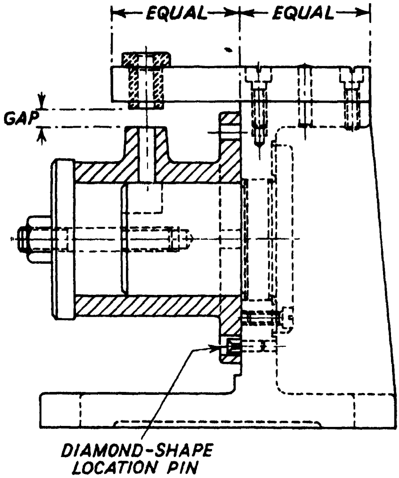


Fig. 18.22

To maintain the correct position of a drill plate to the component location points on the jig body, dowel pins are necessary; in this respect, adequately large pins are recommended, since they are capable of withstanding harsh treatment without movement or distortion. It will be noted in Fig. 18.22 that the length of the base of the jig under the drill plate exceeds that at the rear. This is a feature that should be incorporated in most drilling jigs because the base under the drill plate takes the thrust of the cutting tools. Securing a component into a jig with a screw or bolt through the drill plate is bad practice and should be avoided, even though, on many occasions, it may seem expedient to use this method. By doing so, the drill plate is likely to be loosened from its anchorage when the bolt is tightened.

Designing a Drilling Jig. Let us now consider the design of a jig for drilling the fitting face of the component shown in Figs. 18.17 and 18.18. For a workpiece of moderate size a "turnover" jig should be suitable (Fig. 18.23), and since the jig will require constant handling, lightness should be the prime factor. The fitting face, having been previously milled, would be positioned on to a profile plate secured to the jig and would be $\frac{1}{16}$ in. greater in size than the component, thus allowing for a clear view around the contour of the component. Sometimes it is advisable to provide for two, screwed, adjustable stops *A*, especially if a long face is being profiled, as these provide a means to "square up" the workpiece more easily. Sighting the boss on the component will be carried out by a profile plate similar to the one shown in Fig. 18.14. As the drilling of the flange holes will precede that of milling the sides of the main boss, a check on the setting of the boss will need to be provided for by a second sighting plate *B*. This will ensure that sufficient machining is allowed for so that, when milled to the requisite width, the boss is placed centrally between the two lines of bolt holes. Having performed the operations described above, we are now sure that the component has been equalized or balanced to

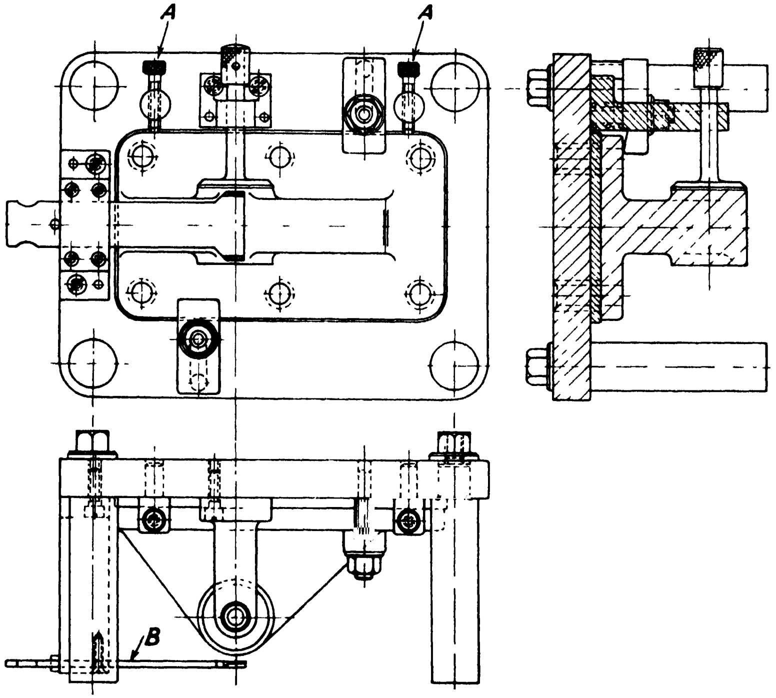


Fig. 18.23

obtain the "best" out of the casting and, therefore, are confident that the holes we are about to drill, after applying the clamps, will be properly related to other operations. Drilling against the clamps, although not a good policy generally, is acceptable on this design of jig, and from experience has always proved satisfactory.

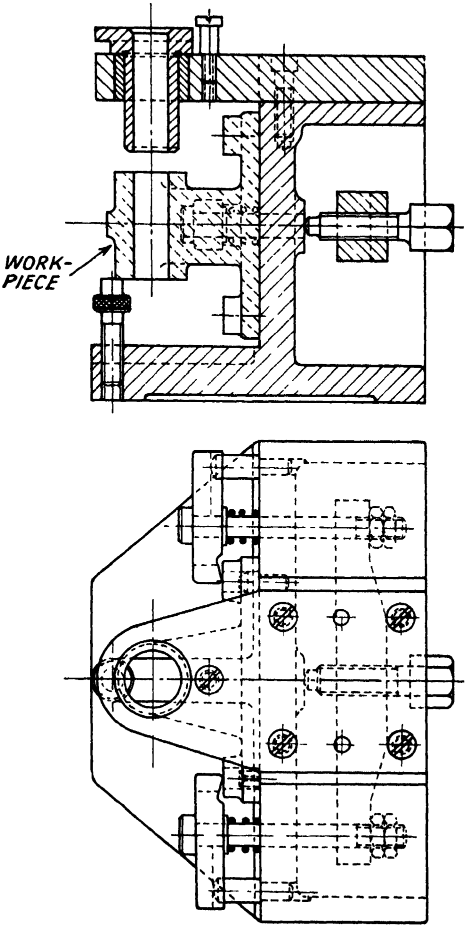


Fig. 18.24

We have already reviewed the method of milling the boss faces to width (*see* Fig. 18.18), and now pass on to the operation of drilling and reaming the hole in the boss. Having drilled the holes in the fitting face, location of the component would be taken from two of these holes, using dowel pins similar to those illustrated in Fig. 18.17.

Clamping the workpiece to the jig may be performed by a compensating clamp, which is an advantage where loading time is a consideration, because this method ensures that the securing effort is applied at both ends of the component simultaneously (Fig. 18.24).

With the flange of the workpiece protruding above the face of the boss, to arrange for the tools to be guided for the extra length, it is permissible to extend the slip bushes to make provision for this feature. The use of a support jack for the fairly long overhang of the boss from the fitting face, may be an advantage.

Milling and Drilling Fixtures. With small quantity production the economics of the tooling must be observed. Equipment which will enable a multiplicity of operations to be performed, will lessen cost without detriment to the finished article. Fig. 18.25

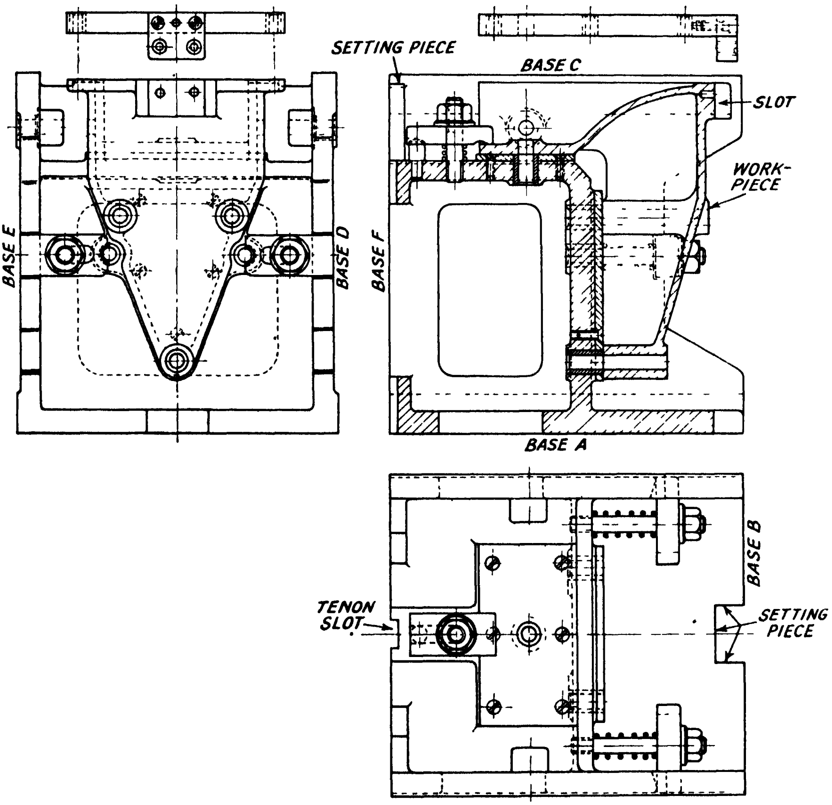


Fig. 18.25

illustrates the equipment for aluminium castings to be both milled and drilled in the same fixture.

For milling the top face of the component, the fixture, seated on Base *A* is arranged on a vertical milling machine, setting the milling cutter to the appropriate setting piece. The right-angled faces have been previously milled, so the component is located in the fixture seated on two profile plates fashioned to the shape of the two faces. The profile plates, which are secured to the fixture body, are $\frac{1}{16}$ in. larger in shape than the workpiece and, therefore, permit a clear sight around the outside contour, although for this milling operation careful setting is not necessary.

For the drilling operation, the fixture, seated on Base *B*, will provide the position for drilling the five holes in the triangular face, while Base *C* will allow for the drilling of one hole in the adjacent face. For drilling the two holes in the side faces, the fixture will be seated on Bases *D* and *E*.

The slot in the component may be milled on a horizontal milling machine, arranging the fixture on the table on Base *F* with tenons suitable for the type of machine, again using the appropriate setting piece for positioning the cutter. To ensure that the slot is milled relative to the drilled holes, the provision of a location pin will be necessary, locating through one of the holes in the triangular face to the bush in the fixture.

For drilling the holes in the top face and slot, a loose drill plate, provided with a suitable location for positioning purposes, would enable the remaining operations to be completed.

Turning and Boring Fixtures, although their number is relatively small, must be mentioned here. The first factor in the designing of turning fixtures is the distance from the centre of the spindle of a turret or centre lathe to the carriage or lathe bed, known as the "swing" of the machine, since this determines the diameter of the fixture. Location of the fixture is normally taken on the spindle nose, this having been suitably provided with a spigot of a standard size, with tapped, or bolt, holes for securing purposes. We should, therefore, design the locating face of the fixture to accept the spigot and retaining screws or bolts. Generally, a cast-iron body is most suitable for turning fixtures as this allows for moulding shapes more acceptable to revolving mechanisms.

An example of a typical fixture, shown in Fig. 18.26, illustrates a component that requires boring, counter-boring and facing. The workpiece is positioned on a machined surface, located by dowel pins, and secured by two clamps, one at each end. It will be noted that the machined surface supporting the component is strengthened by suitable webs and that most of the projections are shrouded by the walls of the fixture casting. For safety, it is essential that very full consideration should be given to the danger of projections either on the fixture or on corners of the component which may project from the fixture.

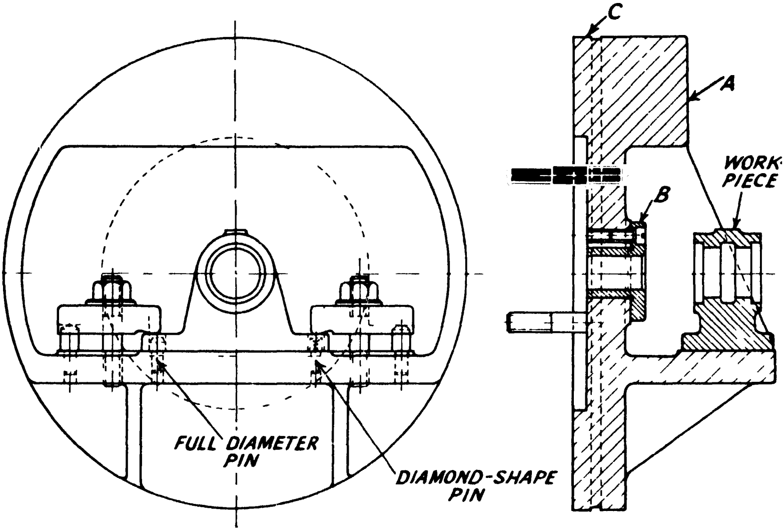


Fig. 18.26

Because most of the weight is below the centre-line of the fixture shown in Fig. 18.26, it is necessary to balance this weight by the addition of a suitable balance weight *A*, which may be calculated within limits. It is often necessary, however, to implement or reduce the balance weight when the fixture is completely manufactured and ready for use. To support or guide the boring bars when cutting, a pilot bush *B* is provided, and this is made a push fit into the rear of the fixture and secured by socket-head screws. A further feature to be provided on turning fixtures is a truing register *C* which enables an operator, by means of a dial indicator, to ensure that the fixture has been correctly positioned on the spindle nose.

Many of the modern lathes are fitted with compressed-air mechanism for the operation of chuck jaws, and it is possible, when the chuck is removed and a fixture substituted, to make use of this device. Fig. 18.27 shows a typical application of the use of this feature. A workpiece is to be turned and faced and is located on a hardened and ground spigot and held in position by a washer *C*. The washer is moved backwards and forwards axially by means of the central rod, which in turn is coupled to the compressed-air mechanism positioned at the rear of the lathe, and provides the necessary movement. By this means, both time and energy are conserved.

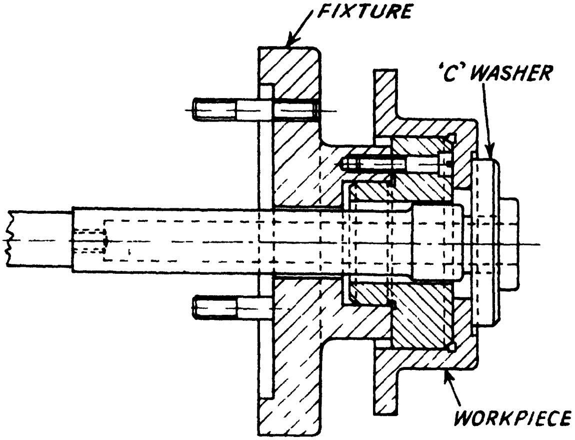


Fig. 18.27

There are many occasions when the size of the workpiece is such that it is impossible to perform the requisite operations on a lathe, and we have then to consider using a vertical boring machine. The functioning of this machine is practically identical with that of a lathe, so that the design of the equipment conforms to the same principles as those for turning fixtures.

Horizontal Boring Machine Fixtures. Fixtures for use on horizontal boring machines differ from those on the vertical type because the work is stationary and the tools revolve, whereas on the vertical type of machine the work revolves and the tools are stationary.

In the design of a horizontal boring machine fixture (Fig. 18.28) many of the features previously outlined with respect to the location and clamping of the workpiece may be embodied, and similar provision may be made for positioning the fixture on the machine table, and, once again, it is probably advisable to make the body of cast-iron. Horizontal boring machine fixtures are usually for large components, so that it is necessary to give special attention to the base and to the provision of suitably-positioned supporting webs, in order that a rigid foundation may be designed with a minimum weight. The space between the workpiece and the boring bar supports should be adequate to permit unrestricted mounting and for the removal of tools, for it is often found that, due to large size of bores or faces being machined, it is not possible to pass the tools through guide bushes on the fixture. Provision must, therefore, be made for the tools to be arranged in suitable heads and offered to the pilot bar in the space allowed for them.

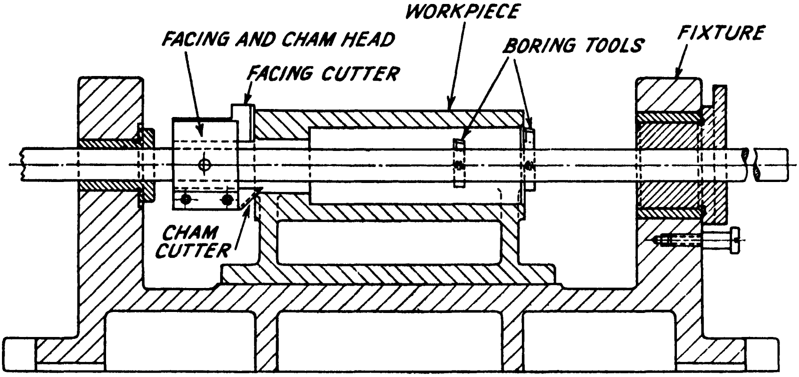


Fig. 18.28

When planning the position of the component in the fixture, it is advisable to arrange for the bores of larger size to be at the rear end, that is at the end farthest away from the spindle, since this often allows the boring tools to be permanently retained in the bar. Slip bushes are used in this method, the bore of the liner bush being large enough to allow the tools and the bar to pass, the slip bush being positioned after mounting. It will be found unnecessary to make provision for slip bushes at the opposite end, and a liner bush with the bore-size suitable for the boring bar is quite adequate.

Broaching Fixtures are usually quite simple in construction, but brief reference is necessary here at least to keyway and spline broaching. Similar to turning lathes, broaching machines are usually provided with a locating medium for the accommodation of fixtures relative to the spindle of the machine, and these should be designed with a size of spigot suitable for the type of machine using the equipment. Considering a component with a centre boss requiring a keyway, location of the workpiece on the fixture would be taken from the bore, taking care to use the face of the boss to withstand the thrust of the broach. The length of the spigot should exceed that of the workpiece, thus ensuring that the first tooth on the broach will have adequate support upon engagement. The slot in the spigot to accept the broach is, of course, dependent on the size of broach being used. It is advisable, if practicable, to provide a wearing strip on the base of the slot, this being an advantage if adjustment to the depth of the keyway is found necessary. Fig. 18.29 shows a typical example of a keyway broaching fixture.

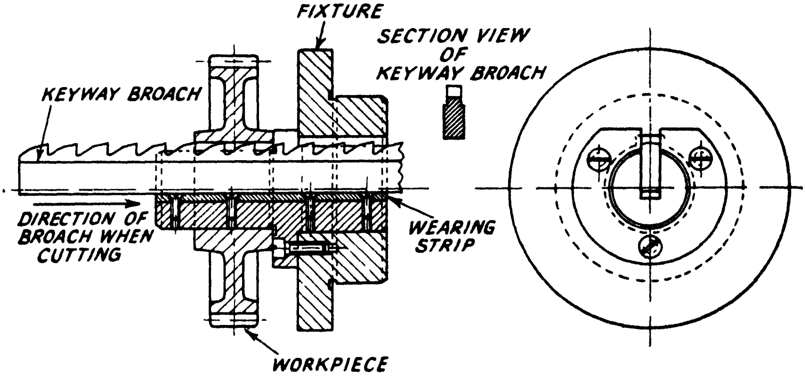

FIXTURE
SECTION VIEW OF KEYWAY BROACH
KEYWAY BROACH
DIRECTION OF BROACH WHEN CUTTING
WEARING STRIP
WORKPIECE

Fig. 18.29

Broaching fixtures for splined bores may be very simple in design, consisting of nothing more than an abutment plate located in the spigot bore of the machine. With the pilot portion of the broach centralizing the workpiece, there is little need to provide location of the component in the fixture unless a relative position of

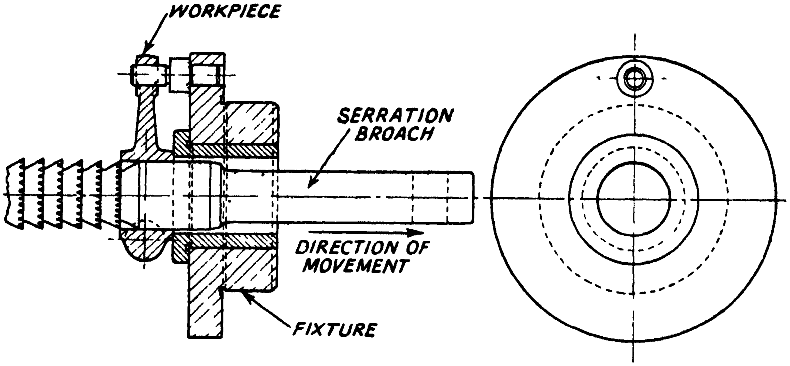


Fig. 18.30

the splines to the profile of the workpiece is called for. Fig. 18.30 shows an example of a component for which an extra location is provided to ensure that the splines in the bore are positioned to the hole in the lever.

For Bibliography see end of book.

CHAPTER XIX

FRICTION, LUBRICANTS AND CUTTING FLUIDS

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Friction. Friction may be defined as the resistance offered to the movement of a body by a surface in contact with it. In the case of static friction, the force necessary to initiate movement is the frictional force, and the ratio between this force and the load that the body exerts on the surface is found to be a constant, which is the coefficient of friction μ.

$$\text{Thus } \mu = F/W \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where F = friction force and W = normal load on surface.

That the value of μ is independent in this way of the load—in other words, that the frictional force is directly proportional to the load—is one of two classical laws of friction, the second being that μ is independent of the apparent area of contact between the mating surfaces. This is explicable by considering the difference between the apparent and the true areas of contact. Mating surfaces are really in contact only at high spots, which represent merely a minute proportion of the apparent area, and these high spots flatten out in direct proportion to the unit load. If the apparent area is changed, but not the load—as for example by up-ending a brick from the flat position—the unit load increases and causes greater flattening, on fewer high spots, until the true area of contact so formed is as before. Both the load and the true contact area being thus unchanged, so also is μ.

The force required to maintain motion (kinetic friction) is usually markedly less than that to initiate motion (static friction), but sometimes they differ very little, and sometimes the kinetic friction is the greater. The relationship can to some extent be controlled by choice of lubricant, and this is important in certain situations, notably the lubrication of slideways (see later under *Slideways*).

Nowadays, friction is attributed to adhesion between the mating surfaces, Bowden and his school at Cambridge having made outstanding contributions to this viewpoint. Though there is still controversy about details, theory today is on the following lines. As already remarked, bodies in contact touch only at high spots, where the high local pressures result in plastic flattening. If motion is now started, intense heat is evolved at the points of contact, and soon the pressure and temperature combined cause local welding. For motion to continue, the applied force must now increase until it shears these microwelds, and this cycle recurs so long as motion continues. Sliding is therefore not truly steady, but consists of alternations of sticking and slipping—conventionally referred to as "stick-slip"—an effect that is readily demonstrable on sensitive friction-measuring apparatuses. The forming and shearing of the welded junctions are not the only bars to motion; there is in addition a "ploughing" component of the frictional force, corresponding to the forcing of the high spots through the mating surface, and most marked when one metal is much harder than the other. The shearing and ploughing forces together comprise the total frictional force. As a result of the microwelding and shearing action, particles of metal are torn from the surfaces, thus accounting for metallic wear. By the use of lubricants, stick-slip and ploughing are replaced to a greater or less extent by shearing of the lubricant film, with corresponding reductions in frictional force and wear.

In the ordinary atmosphere, unlubricated metals slide on each other with coefficients of friction of about 0·5 to 1·5. Under such conditions, however, most metal surfaces normally carry thin oxide coatings which themselves act as lubricant films and thus keep friction down. The friction between chemically clean, unoxidized metals *in vacuo* is greatly in excess of the above figures, and complete welding occurs under quite low loads. On the other hand, the reduction in friction caused by natural oxide films can be still further extended by lubricants. Wear behaviour also is greatly influenced by lubricants, and by the relative physical properties of the oxides and the underlying metal. Where the oxide is comparable in hardness and plasticity to the parent metal, it deforms to a similar degree under load and thus remains as a fairly coherent protective layer. A very hard oxide, such as aluminium oxide, however, is rapidly splintered under load, and plucking and wear of the underlying metal is then facilitated.

THE THEORY OF LUBRICATION

Nowadays it is usual to distinguish three main types of lubrication—fluid, boundary and extreme pressure. Fluid lubrication is the type generally involved in lubricating machine tools and the other machinery in workshops, though there are exceptions, to be noticed later. In cutting operations, on the other hand, lubrication is of the boundary or extreme pressure types, or a mixture of these.

Fluid Lubrication (often termed hydrodynamic, full-film or thick-film lubrication) exists when the sliding surfaces are separated by a continuous film of lubricant. Ideally, the separation of the surfaces should be complete, and though in practice occasional contact between high-spots is liable to occur, the ideal is approached sufficiently closely in well-designed bearings for complete separation to be assumed in studying the friction and lubrication factors concerned.

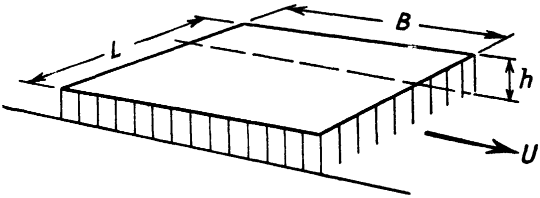

Fig. 19.1 Frictional force between parallel plates separated by a liquid film. (Upper plate moving, lower stationary.)

The forces involved in the relative motion of two parallel plates separated by a liquid are illustrated by Fig. 19.1. When the upper plate moves, a shearing action is set up in the liquid, and force is required to overcome the liquid's resistance. The property of the fluid to which it owes its resistance to shear or flow is known as viscosity, which is fundamentally defined as the force required to shear a layer of fluid of unit area and unit thickness at unit velocity, but is normally expressed in more convenient terms for practical purposes (see later under *Properties*). Towards the end of the seventeenth century, Newton developed an expression for the force opposing the relative motion of the two plates

$$\text{Frictional force} = \eta\, ULB/h \quad . \quad . \quad . \quad . \quad (2)$$

where U is the relative velocity of the plates, L and B the plate dimensions, h the film thickness and η the viscosity coefficient of the liquid.

Irrespective of the values chosen for the quantities represented in the above expression, the system shown in Fig. 19.1 will not carry any load. If, however, one of the plates is slightly inclined to the other, as in Fig. 19.2, a steady load can be supported by the wedge-shaped fluid film when relative movement of the plates takes place.

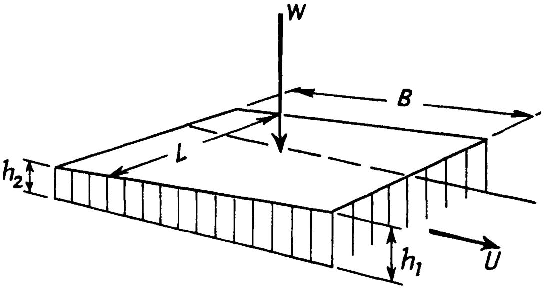

Fig. 19.2 Frictional force and load-carrying capacity of hydrodynamic wedge between inclined plates separated by a liquid film. (Upper plate moving, lower stationary.)

The theory of the wedge action was first evolved by Osborne Reynolds in his classic work of 1886, and he derived the following two important equations:

$$\text{Frictional force} = \eta\, ULB/h_2 \times f\,(h_1/h_2) \quad . \quad . \quad . \quad (3)$$
$$\text{Load-carrying capacity} = \eta\, UL\,(B/h_2)^2 \times f\,(h_1/h_2) \quad . \quad (4)$$

The important points to note are that for satisfactory fluid lubrication there must be a finite clearance between the moving parts, the clearance space must be occupied by a fluid of suitable viscosity, and the geometry of the system must permit the necessary wedge formation. If these requirements can be fulfilled, the great advantages of low friction and negligible wear are obtained.

Figures can be quoted comparing the low values of friction in hydrodynamic sliding with those involved when the surfaces are in contact, but before doing so it is important to emphasize the different nature of the friction losses in the two cases, as indicated by comparing equations (1) and (3). Where contact exists, frictional force is proportional to load and independent of area and speed, so that a coefficient of friction can be derived, as in equation (1), which will be generally applicable to all cases for a particular combination of materials. In a hydrodynamic system, however, the friction force, equation (3), depends on lubricant viscosity, relative velocity of the surfaces, the area of the surfaces and the thickness of the film, but is independent of the load (that is, for a particular geometrical configuration; in practice, variation of the load influences the film thickness so that friction is not completely independent of load). Hence, a constant coefficient of friction, applicable at all loads and speeds, cannot be derived for hydrodynamic systems. However, it has become an accepted convention to divide the sustained load by the friction force for each particular case, and quote the resulting ratio as a kind of "coefficient of hydrodynamic friction", for which common values vary between 0·001 and 0·03. Since coefficients of friction for unlubricated surfaces in contact range from 0·5 to 1·5, the great reduction in friction losses, and the corresponding reduction in heating and wear, when hydrodynamic lubrication can be achieved, are manifest.

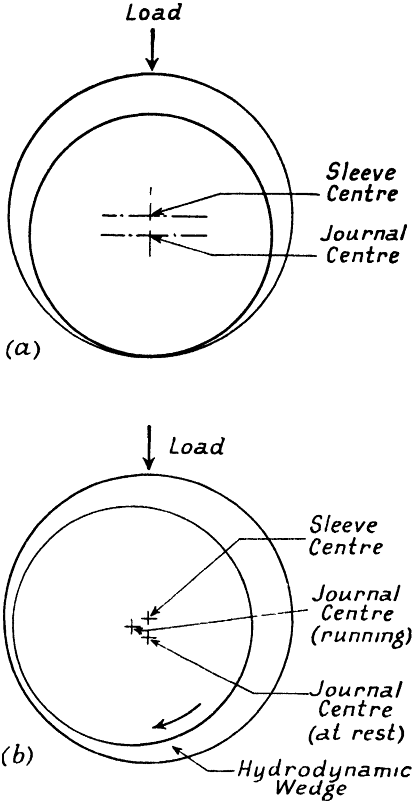

Fig. 19.3. Journal bearing, with shaft under vertical load.
(*a*) At rest. (*b*) Running.

The most important application of full-film lubrication is the journal bearing, illustrated diagrammatically in Fig. 19.3. To enable lubricant to be introduced, there must be a working clearance between the journal and its bearing sleeve. Hence, when stationary, the journal rests on the bottom of the sleeve as shown in (*a*). When running, however, the journal takes up a position as shown in (*b*) from which it will be seen that the clearance space below the journal diminishes in the direction of motion, thus constituting the wedge essential for hydrodynamic lubrication. Many investigations have been made to determine the geometrical position of journals in their bearings and to measure the pressure at various points of the film. The polar diagram in Fig. 19.4*a* shows a typical pressure distribution round the middle of a journal bearing under vertical load, whilst Fig. 19.4*b* shows the pressure distribution along the bearing at its lowest point. The design of the bearing and its oil supply will naturally depend on circumstances, and some of the practical points involved are referred to later.

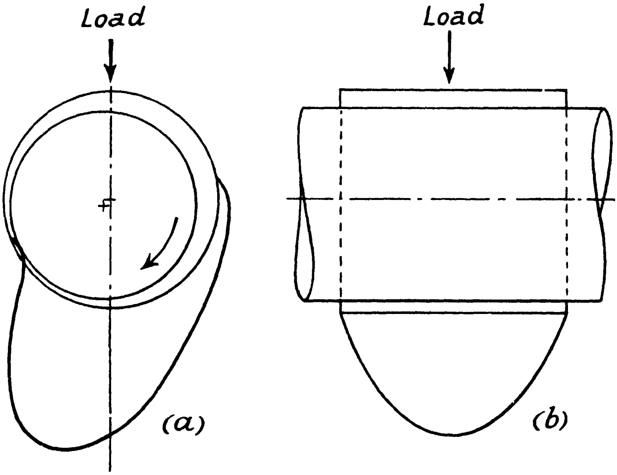

Fig. 19.4. Pressure distribution in journal bearing without oil grooves, with shaft under vertical load.

(*a*) Polar diagram at middle of bearing.
(*b*) Transverse diagram at bottom of bearing.

The application of the hydrodynamic wedge to bearings is also illustrated by the tilting-pad thrust bearing, developed independently by Michell and Kingsbury to overcome difficulties experienced in the propeller-shaft thrust bearings of large ships. This type of bearing is illustrated by Fig. 19.5*a*. A series of tilting pads in the bearing housing is fitted adjacent to the thrust collar of the shaft, and each pad is free to tilt on a pivot as shown in the enlarged sketch, Fig. 19.5*b*. When the shaft is running, the pads automatically incline themselves to the correct angle, and the oil pressure (distributed as shown by the broken line above the pad) is sufficient to carry very heavy loads. The tilting-pad bearing in this form is unlikely to be encountered in machine tools, but similar principles have been applied to journal bearings as shown in Fig. 19.5*c*, and a bearing of this kind is used for the main spindle of one make of grinding machine.

Boundary Lubrication. When the pressures between mating surfaces are high, as in machining and metal forming, for example, a

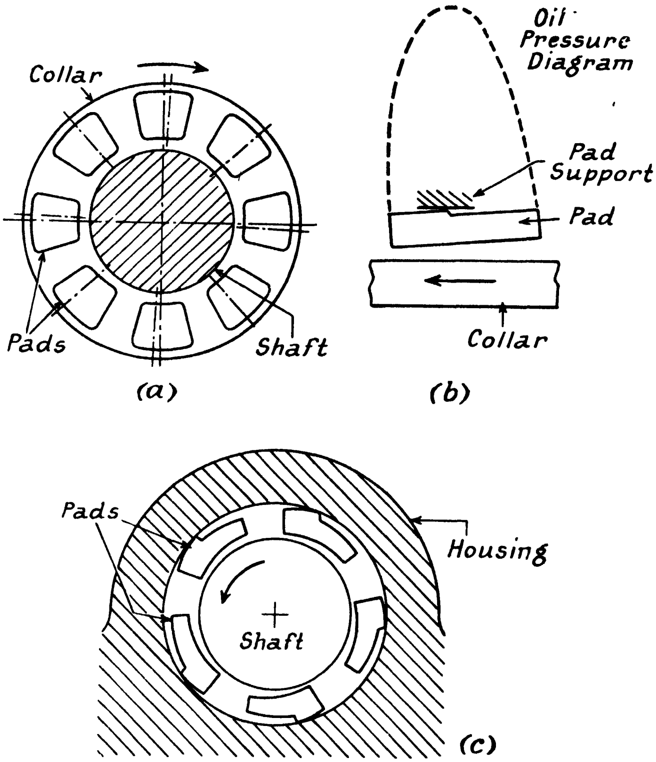

Fig. 19.5. Tilting pad bearings.

(*a*) Thrust bearing. (End elevation, showing disposition of pads.)
(*b*) Thrust bearing. (Detail showing running attitude of pads and oil pressure diagram.)
(*c*) Journal bearing.

point is reached at which thick films of lubricant cannot be maintained, and the films are then often only a few molecules thick. Under these conditions, free flow of lubricant cannot take place; the coefficient of friction is relatively high—between about 0·05 and 0·15, as against 0·001 and 0·03 for fluid lubrication; and there is always considerable wear, caused by the welding and ploughing effects already described, which lubricants reduce but do not eliminate. To limit wear is usually the most important function of boundary lubricants and is best achieved by solids, whether applied as such or formed *in situ.*

The high friction characteristic of boundary lubrication is independent of the viscosity of the lubricant, and of the relative speed of the moving parts, and depend only on the load and the "oiliness" of the lubricant. Oiliness in this sense refers to the ability of certain long-chain molecules to attach themselves to metals in a regular orientated fashion, usually at right angles to the surface like the bristles of a brush. This behaviour was formerly supposed to arise by pure physical adsorption, but it is now thought that the molecules must react chemically with the metal. The molecules able to form such lubricant layers are called polar molecules. Compared with non-polar molecules, polar molecules give lower friction, and result in less wear. The longer the chain length of the molecule, the better the boundary properties—hence, for example, solid hydrocarbons, with their longer molecules, are better boundary lubricants than liquid hydrocarbons of similar type.

Mineral oils contain few polar molecules and are therefore not good boundary lubricants, but fatty oils, or their blends with mineral oils, are very effective, a property they owe largely to their content of free fatty acid, some of which is always present even in highly refined qualities. Fatty acids react with certain metal surfaces to form metallic soaps, which exist as solid polarized layers in contact with the metal, and cause a drop in friction. If the metal is inert to the fatty acid, as some are, the polar properties do not come into play. For example, stearic acid reacts with copper, to form copper stearate, but not with platinum, on which its polar properties are therefore inoperative.

Extreme Pressure Lubrication. When boundary lubrication is so severe as to raise the temperature of the soap (whether separately applied or formed *in situ*) to its melting point, there is a corresponding drop in its effectiveness—the lubricant is said to "break down"—and therefore the higher the melting point the better. Soaps have typical melting points around 120° C. and, provided the system keeps below this temperature, are effective boundary lubricants. In severe frictional conditions, however, this temperature is often greatly exceeded, and the lubrication becomes that of the "Extreme Pressure" type, which can be regarded from some aspects as the upper limit of the boundary type, although it is usually treated separately. Protection against these severe conditions is again given by producing layers of solid substances *in situ*—in this case of chloride, sulphide, or occasionally phosphide, separately or together. E.P. lubricants contain additives that react with mating metal surfaces at points where the high spots are in contact, to form these substances, which are easily sheared and have rather high melting points. The essential condition for effective reaction is not extreme pressure, but elevated temperature (towards which high pressure is merely a means), and the term "Extreme Temperature Lubrication" would therefore strictly be more accurate.

As with the soap and other films providing boundary lubrication, the effectiveness of E.P. films is limited by their melting points which, however, are much higher. Thus, iron chloride films, as formed on ferrous metals, are effective up to about 350° C., and iron sulphides up to about 800° C. This advantage of sulphide films is offset to some extent by their higher shear strength, which makes them tend to give higher friction. By using both types together, useful combinations of properties can be produced.

The range of substances that can be used to produce such films is very wide, but among the most important are chlorinated waxes, containing about 30 to 40 per cent of chlorine, and sulphurized fatty oils, containing about 5 to 25 per cent of sulphur. When combined action is required, some of each type may be added, or a single sulphochlorinated additive, for instance a sulphochlorinated fatty oil, may be used instead.

As E.P. lubricants depend upon high temperatures for coming into action, if they remain cool in bulk they exert their effect only where the relative motion of high spots generates the required heat. In practice, E.P. agents are thus often more localized in effect than typical boundary lubricants such as fatty acids, which generally form soap layers over the whole wetted surface, and at atmospheric temperature. A contrast may also be drawn between fluid E.P. lubricants, and solid lubricants such as talc, mica, chalk and graphite. These bodies possess the high melting points and low shear strength necessary for extreme pressure situations, but their effectiveness is often limited by the difficulty of ensuring that they are present precisely where required, namely, where the high spots come into contact. Again, unlike E.P. lubricants, they do not react chemically with the metal, their action being purely of a physical nature.

Laboratory coefficients of friction of E.P. lubricants tend to be rather higher than those of boundary lubricants such as fats and soaps, but such figures, obtained under relatively light loading, are no reliable guide to service performance, where loading may be in the seizure region. In such applications, the wear with boundary lubricants may be many times greater than with E.P. lubricants. Such conditions occur especially in metal working and in heavily loaded gear systems, and it is in these spheres that E.P. oils find their chief application.

Finally, a word on the interrelation of the three states of lubrication dealt with above—hydrodynamic, boundary, and E.P. As may be supposed, lubrication conditions in practice are not always purely of one type. For example, in many metal-forming operations —rolling is a good example—the state of lubrication seems to include both hydrodynamic and boundary effects. Pressures in rolling are so high, and wear so great, that the conditions cannot be truly hydrodynamic; yet the friction often varies with rolling speed and with the viscosity of the lubricant—effects that prove the state not to be truly boundary. This region of lubrication, about which there is still much to be learned, is often called quasi-hydrodynamic. Again, boundary and E.P. conditions often coexist, notably in machining operations, where the face of the tool may be under E.P. conditions, shading away to boundary conditions elsewhere. In such cases the need for more than one type of additive is evident. For in the E.P. region, boundary lubricants are not powerful enough to be effective; and elsewhere, conditions are too mild to bring E.P. additives into play.

TYPES OF LUBRICANT

Oils. The oils used in lubrication include mineral oils, fatty oils, compounded oils, additive oils, and soluble oils. Only the general characteristics of these will be discussed at this stage, fuller details as necessary being given under *Lubricants for Machine Tools* and *Cutting Fluids*.

MINERAL OILS are produced from petroleum crudes which, though varying widely in composition, all consist of large numbers of hydrocarbons (compounds of hydrogen and carbon) belonging to three main classes—paraffins, naphthenes and aromatics. The crudes are subjected to various treatments, including fractional distillation, dewaxing, deasphaltizing, acid refining and solvent refining. Fractional distillation consists in heating the oil to vaporization, often under vacuum, and condensing the vapours into various liquid fractions, called distillates. From the heavy residues left by certain crudes, other types of oil, called *residual oils*, are produced. Dewaxing and deasphaltizing, as their names imply, are processes whereby wax and asphaltic bitumen, when present, are removed from the oil. Acid refining consists in treatment with sulphuric acid, which attacks and removes the less stable constituents of the oil. The refined oil is then treated with alkali to remove residual acid, and usually also with a decolourizing earth, which removes the dark constituents and gives a measure of control of the ultimate colour of the oil, besides modifying other properties. In solvent refining, the oil is treated with certain solvents in which the desirable and undesirable constituents of the oil have different solubilities, and so can be separated. Important solvents used in various processes of this kind are liquid sulphur dioxide, furfuraldehyde, cresylic acids, and propane. The choice and sequence of the treatments depend on the nature both of the crude and of the desired products, of which the most important are fuel oils, gasoline, kerosene, lubricating oils, paraffin wax, and bitumen. In particular, ranges of lubricating oils varying in viscosity, volatility, resistance to oxidation and so on are produced, and these refinery oils are then used, alone or blended together, and with or without other constituents, for various applications, both in general lubrication and in machining. The ultimate lubricant may be a straight mineral oil, a compounded oil, an additive oil, or a soluble oil.

FATTY OILS are derived from animal or vegetable sources and belong to the class of carbohydrates (compounds of carbon, hydrogen and oxygen). They consist principally of complex mixtures of the glycerides of fatty acids—such as stearic, palmitic, capric and lauric acids, the nature and proportions of the glycerides being characteristic for each fatty oil. Most fatty oils have viscosities of the same order as light machinery oils and, by virtue of their polar nature, they have high "oiliness"—excellent intrinsic properties both for machine lubrication and for machining. Unfortunately, fatty oils suffer from the defects of oxidizing, thickening and sludging very rapidly under working conditions, which makes them unsuitable as a rule for machine lubrication, and though lard oil, rape oil, and others make good cutting oils, they have been almost entirely displaced by compounded oils or E.P. oils, as explained below.

COMPOUNDED OILS are blends of mineral oil and fatty oils such as rape oil or lard oil (3 to 30 per cent fatty oil covers most commercial grades); their lubricating properties are roughly equivalent to those of the neat fatty oil. Sometimes fatty acids, such as oleic acid, are used instead of fatty oils, and the proportion is then usually only from about 1 to 10 per cent. Compounded oils are much less prone to thickening and sludging than neat fatty oils, and can be produced in a wide range of viscosities. These attributes, plus their excellent oiliness, give them very wide usefulness, both as machine lubricants and in machining.

ADDITIVE OILS are mineral oils in which additives have been incorporated to confer special properties of one sort or another to meet particular working conditions, and they play an essential part in many modern engineering advances. The main types of additive are briefly summarized below.

Pour point depressants are added to improve low-temperature flow properties, particularly of paraffinic type oils, which set at inconveniently high temperatures for certain applications. *Viscosity index improvers* confer improved viscosity/temperature characteristics, for instance in multigrade motor oils and in aviation hydraulic oils. *Anti-rust additives* are often used to give protection against rusting in circulating systems where water is entrained, for example in turbine and hydraulic systems. *Anti-foam additives* are for reducing foaming tendencies (often caused, incidentally, by other additives). *Oiliness additives* are polar bodies, which assist lubrication under boundary conditions. *E.P. additives* confer resistance to heavy loads, in regions beyond hydrodynamic or normal boundary conditions, as in certain types of gears and in metal-working. *Anti-wear additives* give a chemical polishing effect, which increases the load-carrying area and so reduces the true unit load and, ultimately, the wear. *Tackinses additives* increase the cohesive and adhesive properties of the lubricant, thereby reducing spattering, and are valuable in textile oils and certain greases. *Anti-oxidants* lessen oxidation of the oil under elevated temperatures of service, for instance in turbines, hydraulic equipment, transformers and I.C. engines. *Detergent additives* are employed to prevent agglomeration of soot and similar bodies in the oil, and so to reduce sludging and lacquer formation—particularly in I.C. engine oils.

Where necessary, more than one type of additive may be introduced, and compatibility of these with each other, and with the oil itself, is an important requirement. As there are many examples of every type of additive, and the search for new ones is incessant, the technology of additive oils has become highly complex. In the field of general lubrication, additives of every type find application, but in machining, only oiliness and E.P. additives are common.

SOLUBLE OILS are blends of mineral oils and emulsifiers which, on mixing with water, form colloidal oil-in-water dispersions (not true solutions, the name being really a misnomer). Soluble oils are important mainly as cutting fluids and as rolling fluids, but are also occasionally used, neat or emulsified, in hydraulic systems.

Greases. Most lubricating greases consist essentially of dispersions of metallic soaps in mineral oils. The soaps cause the oil to gel into the familiar solid or semi-solid condition. Oil is the major constituent, a common figure for soap content being about 15 per cent by weight, although special greases show wide variation from this figure. Other constituents, such as glycerol and fatty acids, may also be present, as stabilizing agents.

Varying the type of soap produces greases with distinctive properties. Thus calcium soaps (used in "lime-base greases"), being insoluble in water, provide water-resistant greases. By contrast, soda-base greases (sodium soaps) are unstable to water, but can be used at higher temperatures than can lime-base. These are at present the two most common types. However, lithium-base greases, which combine water-resistance with marked resistance to high temperatures, and thus can serve as multi-purpose greases, are attracting increasing attention, and aluminium-base greases, which are water-resistant, are also used, though only to a small extent. There are also mixed-base greases, chiefly soda/lime. Each type of grease can be made in several consistencies, usually by varying the soap content, and the oil constituent is also varied, ranges of products to suit different conditions thus being produced. Consistency refers to the degree of solidity of greases, and is a valuable, though empirical, indication of resistance to permanent change of shape. It is commonly measured as the depth to which a standard cone penetrates into the grease in five seconds.

In addition there are many special greases. The E.P. greases contain a proportion of extreme pressure agent to increase the load-carrying capacity; and other greases contain graphite, or molybdenum disulphide, for high temperatures. In other special greases for high temperatures, the mineral oil is replaced by synthetic oils such as silicones, or the soap by inorganic gelling agents such as special clays.

Generally speaking, greases are inferior as lubricants to oils, but are often more handy, for example where access is difficult or where oil cannot be properly sealed in. Such applications vary widely, from the bearings on small electric motors, to the hot, heavily loaded bearings in steel mills, for instance.

Special Lubricants. The number of substances that are used to a limited extent as lubricants is extremely high. An exhaustive survey is not possible here, but some of the most important are briefly described below.

Graphite has the ability to adhere strongly to metal surfaces, and its excellent lubricating qualities appear to be due in part to its plate-like structure, in part to adsorbed moisture films. It is available either in the flake form or as a colloidal suspension in water or oil, and may be used directly in these forms. Alternatively, the flake graphite, or the colloidal suspension in oil, may be blended with oil or grease to give graphited oils and greases. These find considerable application, especially in high-temperature situations, such as on the moving parts of furnaces, or in hot metal forming, where graphite's property of remaining effective as a lubricant up to temperatures of over 600° C. is invaluable. In high-temperature applications, the petroleum product serves essentially as a carrier, and burns away to leave a film of graphite. Graphite's insolubility and black colour militate against its wider employment at normal temperatures, though here too it is sometimes valuable. Although not unknown in cutting fluids for special operations, its use here is rare.

Molybdenite (*molybdenum disulphide*, MoS_2) has recently attracted much attention as a special lubricant, akin to graphite in both merits and defects. Like graphite, it has a plate-like structure, is available in flaky and colloidal forms, is black and insoluble, and adheres strongly to metal surfaces, giving a low coefficient of friction. It is particularly valuable for high-temperature work, where it has the advantage over graphite of in no way depending for its lubricating effect on the presence of adsorbed moisture. On the other hand, molybdenum disulphide starts to decompose at about 400° C. into molybdenum trioxide (which is abrasive) and sulphur dioxide (which is corrosive). Above this temperature, therefore, graphite, which does not decompose until 450–650° C., and then only into harmless carbon oxides, has advantages.

The lubricating properties of molybdenum disulphide may include E.P. effects due to its sulphur content, and it is claimed to be very effective in preventing seizure under high pressures. Its higher specific gravity (about 5) makes it more liable than graphite to separate out of suspensions. This difficulty can be avoided by using a pre-treatment that binds the molybdenum disulphide to the working surfaces, a method that has often proved effective. Though mainly used in general lubrication, it is also occasionally valuable in special machining applications.

Talc, Mica and Chalk, in the finely divided form, are often incorporated in drawing compounds, where they act to form solid layers of low fusibility that hinder scoring and welding. Drawing compounds of this kind are occasionally used in machining operations, for instance broaching, but, as with all insoluble solids, their use is restricted by difficulties of application and removal. Fillers are also sometimes incorporated in greases, but in this case merely for cheapness. Talc and mica are also used in lapping.

SYNTHETIC LUBRICANTS, which have very useful properties, often markedly different from those of normal lubricants, have been developed in many varieties in recent years, the following being outstanding examples.

Silicones are organosilicon oxide polymers (polymers are substances whose molecules are very large, being formed by the aggregation together of many small molecules). In the silicones, the element silicon functions in an analogous way to carbon in ordinary organic chemicals, complex molecules being formed by the self-attachment of successive silicon atoms. The silicones are available as liquids, semi-liquids, and solids. One of their outstanding properties is that their viscosity is much less sensitive to temperature than that of mineral oils. For example, even a relatively insensitive mineral oil, when lowered in temperature from 120° C. to − 25° C., becomes about a thousand times more viscous, whereas the corresponding figure for a silicone fluid is only about seventeen times. Good temperature-viscosity characteristics such as this can be of great value where lubricants experience wide temperature variations. Other valuable properties of silicones are good oxidation stability, very low pour point, and low volatility. On the other hand, they are not good boundary lubricants, and are therefore used chiefly where lubrication itself is not very exacting, but good temperature-viscosity characteristics and stability are especially important. Examples are as liquids in vacuum diffusion pumps; in greases for lightly loaded anti-friction bearings; and as lubricants for taps and joints.

A special use of certain silicone fluids is as anti-foaming agents, especially in mineral oils, where a few parts per million are often very effective, the dispersed particles of silicone acting as bubble breakers. Silicones to limit foaming in aqueous media are also available.

Synthetic esters are now produced in considerable variety. Esters, which are compounds of acids and alcohols, occur widely in nature, for example in fatty oils, but other types of ester with special properties are now synthetized. One type (of which di-2-ethyl hexyl sebacate is an example) is characterized by good viscosity-temperature characteristics, together with better boundary properties and lower volatility than mineral oils of similar viscosity. This type is therefore useful at high and low temperatures, and hence finds applications in aircraft oils and greases. Again, the esters of phosphoric acid are of very low flammability, which leads to their use in aviation hydraulic oils.

Polyalkylene glycols are a group of non-hydrocarbon polymers produced in a wide range of viscosities, and in water-soluble and water-insoluble qualities. They possess good temperature-viscosity characteristics and find application as hydraulic oils and in special greases.

Halogeno-hydrocarbons are hydrocarbons in which the hydrogen atoms have been partly or wholly substituted by fluorine or chlorine atoms, or in some cases by a mixture of both. The outstanding merit of the liquid varieties is their high chemical and thermal stability—their demerits are poor viscosity-temperature characteristics and high volatility. So far they have mainly been used in applications where high thermal and chemical stability is particularly important, as in non-inflammable hydraulic aviation oils.

This class of substances also includes solid materials consisting of carbon and halogen, of which Teflon is the best known. Teflon and Fluon are commercial names for polytetrafluoroethylene (PTFE), which as the name implies contains fluorine, and which gives remarkably low coefficients of friction as a metal lubricant, and is effective up to the usefully high temperature of about 320°C. So far, PTFE is little used in industry, partly owing to cost and partly to the usual difficulty of applying solids effectively, but it is valuable on a small scale when particularly low friction is desired, as for example in instrument work. One method of use is as a surface coating in conjunction with a liquid, which may be oil or water.

LUBRICATION OF MACHINE TOOLS

Machine tools must be robustly constructed to minimize deflection and vibration, hence loadings on bearings, gears and slideways are generally moderate, and lubrication is thereby simplified. There are, however, requirements (such as those imposed by high-speed spindles or slow-moving tables) which must be satisfied if accurate trouble-free operation with minimum wear is to be ensured.

Most parts of a machine tool can be lubricated satisfactorily by a mineral oil of suitable viscosity. In addition to lubricating, however, the oil must perform other functions such as cooling bearings and gears, and protecting the machine parts from corrosion, and it must itself resist deterioration. Care must therefore be taken to select mineral oils of the necessary quality, particularly for the circulating systems which are now widely used. In such a system, the oil becomes heated in the bearings and gears, and is subject to some churning and spraying, so that it repeatedly comes into contact in a finely divided condition with air. This state of affairs is conducive to oxidation, which tends to produce organic acids and sludge in the oil. It is therefore important to use an oil which is stable and of good resistance to oxidation. Moisture is also likely to find its way into lubricating oil systems from the atmosphere or by ingress of soluble cutting oils, so that the oil should have good "demulsibility," to permit quick separation of water in the sump.

For these reasons solvent-refined oils, with their high stability, are generally recommended, and they give long and satisfactory service, provided reasonable care is paid to general cleanliness, filters, and shaft seals and to minimizing contamination by metallic dust, dirt, and cutting oil.

Bearings. Both plain and anti-friction bearings are widely used in machine tools. There has been an increasing tendency in recent years to replace plain bearings by ball or roller bearings, especially for general-purpose machines of all categories, but the sleeve bearing is still considered essential for the main bearings of some widely different types of machine, notable examples being large lathes and boring mills on the one hand and small precision lathes on the other.

Plain Bearings. As shown earlier, the load-carrying capacity and frictional force of a hydrodynamic bearing are dependent on its dimensions and speed, on the proportions of the hydrodynamic wedge, and on the viscosity of the lubricant. The rate of dissipation of heat is also important since it influences the operating temperature of the oil, and hence its viscosity. The complete relationship between the various factors is therefore so complex that rigorous design of bearings is difficult, and machine tool designers find it more convenient to rely on an intelligent appreciation of existing good practice.

It is, however, as well to be aware of the significance of the ZN/P ratio, both as a help to design and a guide to performance. in this dimensionless ratio Z = absolute viscosity, N = r.p.m. and

P = unit pressure on the projected area of the bearing. If the permissible limits of ZN/P are known for a certain type of bearing, it is then possible to check its suitability for proposed combinations of speed and load. Experimenters have found it useful to plot the so-called coefficient of friction of a bearing (i.e. F/W where F equals circumferential friction force due to viscous shear in the lubricant film and W equals total load on bearing) against ZN/P as shown in Fig. 19.6.

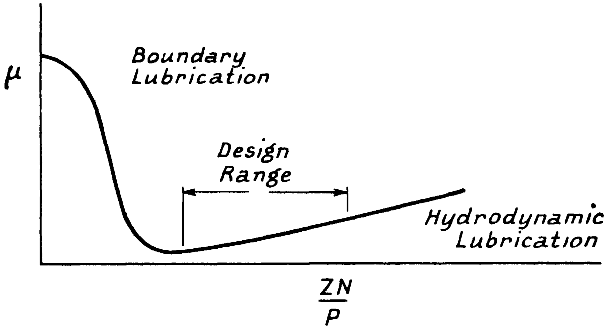

Fig. 19.6. Influence of $\frac{ZN}{P}$ ratio on coefficient of friction.

It will be seen that the coefficient of friction (μ) is high for low value- of ZN/P but quickly drops to a minimum as hydrodynamic lubris cation is established, and then rises again, but much more slowly. In practice, designers endeavour to work in the design range marked in Fig. 19.6 so that they can be sure of operation in the hydrodynamic region and yet avoid undue friction and heating. This, of course, refers to steady running conditions, since all bearings must run through a region of low ZN/P when starting, with boundary lubrication gradually giving way to hydrodynamic as speed rises.

The importance of viscosity is obvious from the above and, provided this is correctly chosen, excellent lubrication is obtained with straight mineral oils. For machine tool applications suitable viscosities range from about 35 sec. Redwood I at 140° F. for high-speed spindles to about 150 sec. Redwood I at 140° F. for the bearings of large heavy-duty machines operating at low speeds, and such oils are in the lower range of commercial viscosities, as is seen from the table given under *Properties of Lubricating Oils* (where, also, the Redwood and other systems of viscosity measurement are defined).

It is common practice to cut oil grooves in bearings, but they are not always properly located. The pressure diagram shown in

Fig. 19.4 must be borne in mind otherwise there is a serious risk of letting the oil escape from the vital zone instead of feeding towards it. This is illustrated by the two diagrams in Fig. 19.7. At (*a*) is shown the unfortunate effect of an oil groove cut at the lowest point of a vertically loaded journal bearing, at (*b*) the less dangerous but still undesirable influence of a central circumferential (360°) groove.

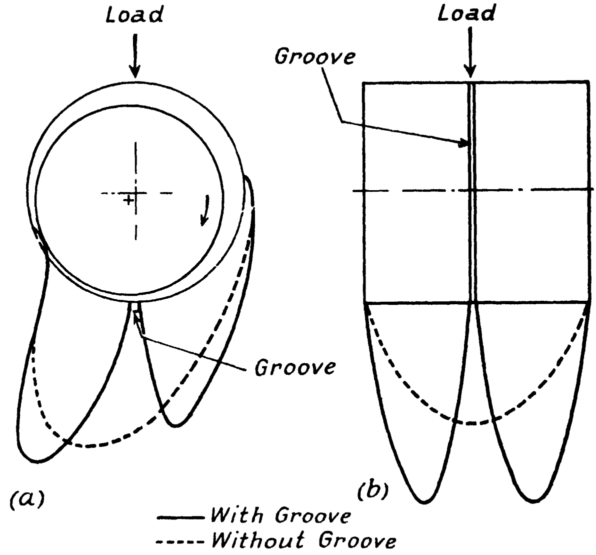

Fig. 19.7. Influence of oil grooves on oil pressure distribution.

(*a*) Transverse groove in loaded zone.
(*b*) Peripheral groove round middle of bearing.

Elaborate grooves are quite unnecessary and a single axial cut in the low-pressure region of the bearing is normally quite adequate, but the designer must remember the direction in which the bearing will be loaded—it may well be upwards in a machine tool. Excellent results have been obtained on high-speed bearings with only a small oil hole and no grooves, suggesting that frequently the main function of the grooves is not to improve lubrication but rather to increase the rate of flow. This improves the cooling, an important function of the lubricant in all high-speed bearings, and particularly so in machine tools where it is essential to minimize the changes in machine alignment that result from warming up.

For the sake of workpiece accuracy, it is desirable to keep the clearance as small as possible, and it is therefore usual to adopt the minimum permitted by the surface roughness and geometrical accuracy commercially practicable for the type of machine concerned. Plain bearings for high-speed precision grinding-machine spindles are of particular importance, and all makers pay great care in the design and manufacture of the bearing and its associated oil supply to maintain a close clearance under all conditions of running. One well-known example embodies a loading device for the top bearing cap, and another embodies a form of the tilting-pad principle already illustrated in Fig. 19.5*c*. For bearings of these types a highly refined mineral oil of high viscosity index and a viscosity of about 50–70 sec. Redwood I at 140° F. is most suitable.

So far reference has been made to oil lubrication only, but greases are occasionally used for journal bearings of secondary importance where there is some advantage in dispensing with special feeding arrangements or where hand oiling would be difficult. For such purposes a general-purpose cup grease of medium or soft consistency is suitable. Even in this limited sphere there is a tendency to abandon grease lubrication and use instead "self-lubricating" bearings, i.e. bearings which consist of porous sleeves impregnated with a suitable oil.

Rolling Bearings. Ball and roller bearings are often used in preference to plain bearings because of their low friction, moderate dimensions, lesser liability to suffer from wear or incorrect adjustment, and ease of replacement when necessary. If suitably selected for the loads and speeds involved, and correctly aligned and assembled, they will give long trouble-free life provided their lubrication requirements are understood. These requirements are: to reduce friction; to protect the bearing surfaces from corrosion; to carry away heat when necessary; and to exclude foreign matter. The need to reduce friction is not always realized. Apart from the friction between the rolling elements and their locating cage (and between cage and race in bearings with race-located cages), considerable friction occurs between the rolling elements and the races, because the theoretically desirable point contact or line contact of ball or roller is not attainable. In practice, there is perceptible deformation of rolling elements and races: contact is therefore made over an area and consequently some sliding must take place. If no lubricant is present, the friction soon causes overheating and damage even at moderate speeds and loads. A small amount of lubricant, however, is sufficient to avoid this, since it appears to be trapped between rolling element and race, despite the very high pressure in the contact area, and minimizes metal-to-metal contact and friction.

Oil lubrication is used in most machine tool applications, common practice being to feed it to ball and roller bearings from central circulating systems (as for example in many lathe headstocks). A straight mineral oil of about 70–140 sec. at 140° F. is normally satisfactory, subject, of course, to the usual requirements of resistance to oxidation and so on. It is essential to see that only a small amount of oil of the proper viscosity is supplied; any increase in either quantity or viscosity only leads to overheating through needless churning.

Although greases are only occasionally used for the lubrication of main spindle bearings, they are widely employed for rolling bearings in feed mechanisms and so on, and are almost invariably used for the bearings of electric motors. The type of grease selected depends on the requirements for resistance to high temperature, water resistance, etc., on the lines already outlined under *Greases*, but usually high stability soda soap greases are most suitable for electric motors, general-purpose lime soap greases for auxiliary mechanisms, and a sodium or lithium soap grease containing an oxidation inhibitor for the rather special cases where grease lubrication is used for high-speed main spindles.

A third method of lubricating rolling bearings is by oil-mist. Various forms exist, the commonest being that in which the oil is first atomized and then carried into the bearing by compressed air. The necessary small quantity of oil is thus readily introduced to the bearing with the minimum churning loss, and with the additional benefit of an air stream to cool the bearing and keep out particles of foreign matter. This system is therefore particularly suitable for small high-speed grinding spindles which must run at speeds of 60,000 r.p.m. or more. Corrosion difficulties may occur due to the moisture often present in compressed air, and it is therefore advisable to use an oil containing a corrosion inhibitor.

Gears. Straight spur, helical, bevel and worm gears are widely used in machine tools, and require the correct application of oil for lubricating and cooling. Sliding occurs between the contacting teeth to varying degrees with all types of gears, and the lubricant must minimize as far as possible the friction, wear and temperature rise in the heavily loaded contact zone to give smooth operation, low losses and long life.

Generally speaking, machine tool gears are not highly rated and a straight mineral oil of moderate viscosity (70–140 sec. Redwood I at 140° F.) can be used. It is therefore possible to lubricate the gears with the same oil as for main and drive bearings, but the churning and temperature effects involved make it particularly important to use only a highly refined, chemically stable oil if long life without deterioration is to be attained.

There are a few cases where the gear lubrication requirements are sufficiently severe to require an oil of higher load-carrying capacity. An example is provided by the main worm drive of high-speed planers. Because of the high sliding loads involved, worm gears always require careful lubrication, and the continual acceleration, deceleration and reversal of the planer drive add to the demands on the lubricant. Such a drive is therefore likely to require at least a high-viscosity mineral oil (e.g. 600 sec. Redwood I at 140° F.) and in some cases a high-viscosity compounded oil is necessary.

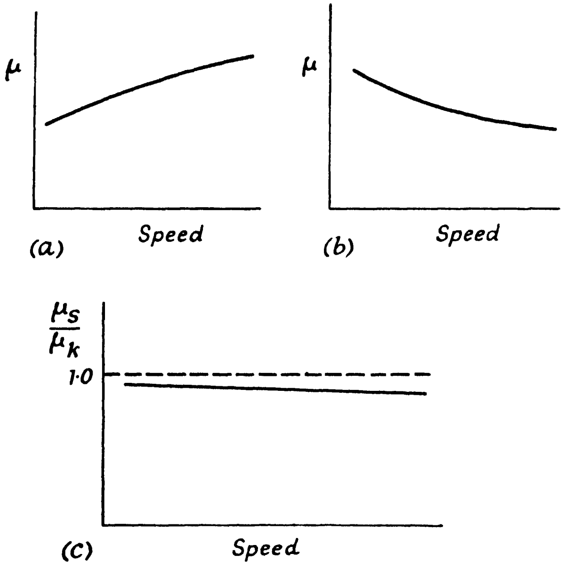

Fig. 19.8. Friction characteristics of tableway lubricants.

(*a*) Friction increasing with speed.

(*b*) Friction decreasing with speed.

(*c*) $\frac{\mu s}{\mu k}$ ratio for a satisfactory tableway oil.

Slideways. In the past it has been usual practice to lubricate the various sliding surfaces of machine tools with the lubricating or hydraulic oil used elsewhere in the machine. However, slow-moving slides and tables sometimes do not operate with the smooth uniform movement required to produce high-quality work. Special lubricants, known as tableway oils, have therefore been introduced, and they provide an interesting example of the development of a lubricant to overcome a specific difficulty.

The trouble is a particular case of the "stick-slip" motion described earlier, and is the result of an unfavourable combination of friction conditions and design factors. It has been shown that "stick-slip" can be prevented by controlling design variables such as mass of sliding body, modulus of rigidity of feed mechanism, damping forces and so on, but this is difficult to arrange for all operating conditions. In practice it has proved more convenient to alter the friction conditions, and prevent "stick-slip" by using a lubricant which ensures that static friction is less than kinetic, that is, friction increases with speed as shown by Fig. 19.8*a* instead of decreasing with speed (the more usual case) as in (*b*). Expressed in terms of the two coefficients, this requires that the ratio of the coefficient of static to that of kinetic friction (μ_s/μ_k) should be less than unity.

A number of boundary lubricants have been shown to satisfy this, and Fig. 19.8*c* shows the ratio μ_s/μ_k for a special tableway lubricant.

Hydraulic Systems are widely used for the operation or control of machine tool assemblies such as grinding-machine tables, and the advantages of wide, stepless speed variation, smooth operation, and close control by manual or automatic means make it likely that the use of such systems will become still more popular.

The minimum requirements of a hydraulic fluid are that it should be virtually incompressible and sufficiently fluid to permit efficient transmission of power, and water would be the obvious choice if no other requirements had to be satisfied. In practice, its promotion of rust and lack of lubricating power make it quite unsuitable for precision machinery, and fluids based on mineral oil are generally preferred. Up to 4000 p.s.i. the compressibility of oils is only about 0·5 per cent per 1000 p.s.i. and a wide range of viscosities is available. Suitable oils also protect the mechanism against rust, minimize the friction between moving parts, and act as their own low-friction seal in the fine clearances necessary in complex, high-pressure control systems. Finally, the hydraulic oil is often suitable for the general lubrication of the slideways and bearings of the machine tool.

A typical hydraulic fluid has a mineral oil base of suitable viscosity (generally 55–70 sec. Redwood I at 140° F. for machine tool purposes) and should have a high viscosity index to avoid too great change of viscosity with temperature. The base should also be highly refined, so that it will have good demulsibility and quickly eliminate any water picked up in the system, and be chemically stable to resist oxidation. The effect of heating and agitation in the presence of air and metallic catalysts is of particular importance in hydraulic systems, where even slight deterioration of the oil can upset the smooth working of the control gear, and it is therefore usual to enhance the oil's resistance to oxidation by an inhibitor. Similarly, the prevention of rust is essential, and though the good oxidation stability and wetting power of suitable oils are valuable in this respect, the addition of a rust inhibitor is advisable. Finally, experience has shown that the addition of an anti-foam agent eliminates occasional trouble which might otherwise arise.

Methods of Application. A lubricant cannot function effectively unless it is systematically applied. The ways in which this may be done can be roughly classified into four main types:

Manual. Lubricants can be applied directly from a can to oil holes on bearings and slides or by hand gun to appropriate oil or grease nipples. There are still cases where oil must be directly applied to slides or open gears but fortunately such crudities are fast disappearing. Manual methods can give quite satisfactory results, but it is difficult to ensure that the correct lubricant finds its way in appropriate quantity to the desired spot at the right time—and free of contamination.

Reservoir systems. Greater reliability under practical conditions can be obtained by using some form of reservoir with simple feed devices, such as drip-feed or siphon-feed lubricators, ring-oilers for journal bearings, or oil-baths for gearboxes. Since these normally incorporate a sight glass indicating the oil level, replenishment is unlikely to be delayed until it is too late. A word of warning should be given against excessive zeal: overfilling of oil-baths can lead to unnecessary churning and overheating.

Pump systems. Here also reservoirs are used, but in conjunction with pump feed to strategic points. Such systems are common in lathe headstocks: a pump connected to the drive system draws oil from a sump and feeds it to a distribution tray at the top of the gearbox, from which it is distributed by pipes and oilways to bearings and gears, and finally drains back to the sump for recirculation.

There is also a "one-shot" system in which a hand pump is operated, say once daily, to supply sufficient oil through a comprehensive feed system to the required spots. This is particularly suitable for those parts of a machine which cannot be conveniently incorporated in a circulating system and have to be lubricated by "total loss" methods.

Automatic systems. Automatic systems have been developed from the pumped systems. Pumps (which may be driven from the gearbox, or operated at each reciprocation of a machine table) supply oil through a system of metering valves in accurately measured quantities to every point requiring it, and both "circulating" or "total loss" methods are used. Though high in first cost, such systems are most satisfactory and are being increasingly adopted.

CUTTING FLUIDS

Functions and Properties. In machining operations, considerable quantities of heat are generated by surface friction and the internal friction of chip deformation, and the intense pressures involved cause rapid wear of the tool. The main functions of cutting fluids are to counteract these effects, by providing cooling and lubrication. By their cooling action they help to maintain the hardness of the tool, and thus to lengthen its life; they also thereby minimize distortion of the workpiece. By their lubricating action they lessen the surface friction (and so also the amount of heat evolved), and also hinder the welding together of chip and tool, thus promoting longer tool life and smoother surface finish.

Cooling power depends mainly upon viscosity, specific heat and wetting ability; anti-friction power (oiliness) upon polar properties; and anti-welding power upon E.P. properties. Various secondary properties are also important. Cutting fluids should not be corrosive to machine tools or workpieces, and should also give some protection against atmospheric corrosion; should be reasonably stable, chemically and physically, in storage and in service; should not smoke or volatilize excessively in use; should not cause blocking of feed pipes nor gumming of slideways; and should preferably be more or less transparent, to facilitate observation of the work. They should also give minimum interference with general lubrication of the machine. Finally, they should not be physiologically harmful, a most important point because their degree of contact with the operative is inevitably considerable.

The importance of cutting fluids varies with the application. On easily machinable metals their contribution is limited, and they are then often dispensed with, for example on soft brass and on magnesium alloys. At the other end of the scale are operations, such as the broaching of gas turbine materials, that are next to impossible without special cutting fluids. In between come numbers of applications where they offer valuable, though limited, technical and economic advantages.

Types. Cutting fluids may be classified as follows: *Aqueous Types:* Soluble Oils (opaque, clear, and E.P.), Water-base Fluids. *Oil Types:* Mineral Oils, Fatty Oils, Compounded Oils, E.P. Oils.

AQUEOUS TYPES of cutting fluid are characterized by generally being supplied as concentrates, which are highly diluted with water to give the cutting fluid actually used on the machine. Consisting thus, as they usually do, of about 80 per cent or more of water when put into use, they possess very high cooling power.

Soluble oils, on mixing with water, give the dispersions of oil in water referred to in workshops as emulsions, slurries, or suds. Fundamentally, soluble oils are blends of a mineral oil and an emulsifier, but typical modern varieties usually contain more than one emulsifier, and possibly other constituents such as wetting and anti-foaming agents. These complications are necessary to produce balanced compositions that are satisfactory as to stability, emulsifiability, anti-corrosivity and so on. Generally at least one of the emulsifiers is a by-product of petroleum refining, the most common being sodium naphthasulphonates, whose calcium analogue has good aqueous solubility, so that hard water causes less trouble than with emulsifiers of the metallic soap type. Consequently, with sodium naphthasulphonates as the predominant emulsifier it is usually unnecessary to soften the water used for making the dispersions, unless it is exceptionally hard.

Soluble oil dispersions have somewhat less cooling power than water itself, but the oil phase gives them a measure of lubricating power, and also suppresses, to a greater or lesser degree, the corrosive tendencies of the water. Dispersions of good-quality oils do not corrode the machine tool or the workpiece, and even protect the freshly machined surfaces for a day or two, though not for long periods, or under severe conditions.

The most common type of soluble oil, widely used in machine shops for a variety of operations, is the opaque soluble oil, which is so called because its emulsions appear opaque and milky, an effect due to the scattering of light by the particles of dispersed oil. Typical opaque soluble oils contain about 70 to 90 per cent of mineral oil, the remainder consisting of emulsifiers and other additives. Commercial grades vary widely in the type and proportion of emulsifier, with resulting wide differences in emulsion stability. Another type of soluble oil, used chiefly for grinding, gives translucent dispersions and is therefore called a clear soluble oil. In clear soluble oils, the ratio of emulsifier to mineral oil is considerably higher than in opaque oils, and, the oil particles in the aqueous dispersion being consequently smaller, they do not scatter light to the same extent—hence the translucency. Translucency gives a better view of the work, but as the dispersed oil gradually agglomerates the emulsions ultimately become rather opaque. Another advantage of clear oils is that "loading" of grinding wheels by oil and swarf is minimized, and wheel dressing can therefore be less frequent. Clear soluble oils can also often be used at lower dilutions than opaque types for similar applications. In spite of these advantages, the clear oils are used much less than the opaque, which are cheaper and are adequate for most purposes. Selection should be guided by assessing performance versus price for the particular application.

Soluble oils are generally used at concentrations of 2 to 10 per cent, according to the application, but concentrations outside these limits are occasionally adopted. Because of their effectiveness (due mainly to their cooling power), cheapness and cleanliness, they are the most widely used of cutting fluids.

A third and more recently developed type is the E.P. soluble oil, in which is incorporated a proportion of E.P. agent, usually of a sulphurized, chlorinated, or sulphochlorinated type. This augments the lubricating power, so that the emulsions give better tool life in certain applications than those of normal soluble oils. Of course, where performance is dominated by the cooling factor, E.P. soluble oils have no advantages over the normal types; and as their E.P. properties are inevitably much lower than those of straight E.P. cutting oils, they do not equal these for severe operations. However, they can be valuable in cases where normal soluble oils are inadequate as lubricants, and straight E.P. cutting oils as coolants, for example in some operations in chucking automatic lathes.

Although emulsions at their best do not merely not cause rusting, but actually afford anti-rust protection, the existence of a largely aqueous fluid in contact with ferrous materials necessarily involves some risk of corrosion. Compared with early varieties, modern soluble oils are greatly improved in anti-corrosion properties, but cheap qualities are often poor in this respect and, if they cause serious corrosion on expensive machine tools, their use is false economy.

Passing mention may be made here of emulsifiable cutting compounds, which as supplied are pastes of buttery consistency and, like soluble oils, are diluted with water for use. The original compound is usually a mixture of fatty oil, soaps, free fatty acid, and water, but mineral oil, and fillers such as talc or mica, may also be present. Though better lubricants, the emulsions are more difficult to prepare than with soluble oils, and are more liable to foaming. However, they are occasionally used in machining for operations as diverse as grinding and broaching. Their main use in machine shops, however, is in presswork, where they are most important lubricants, and are used neat or diluted, according to the severity of the operation, on steel, brass, copper, aluminium and other less important metals. They are also used in other metal-forming processes, notably wire drawing, tube drawing and bar drawing.

Water-base fluids are aqueous solutions of chemicals which are diluted further with water for use in machining. They represent an important improvement on the simple aqueous solutions (of sodium carbonate, trisodium phosphate or soap) which have long been familiar as grinding fluids, but which had largely given place to soluble oils. The formulae are often complicated, and may involve synthetic wetting agents, but usually contain sodium nitrite as one constituent. The cut-backs have high wetting (and therefore cooling) power, strong anti-rusting properties and, in grinding, cause minimum loading of the wheels. These properties, plus their high transparency, make water-base fluids effective alternatives to soluble oils.

OIL-BASE CUTTING OILS may be defined as those containing no water, and they comprise mineral oils, fatty oils, compounded oils, and E.P. oils. The terms straight or neat cutting oils are commonly used to distinguish them from aqueous types. All have much the same specific heat (about 0·5) and therefore at the same viscosity essentially equal cooling power, which, however, is always much less than that of aqueous cutting fluids. Considerations of cooling power, volatility, and oil losses cause viscosities in the range 50–70 sec. Redwood I at 140° F. to be generally used, but there are exceptions. At the one extreme, very light-bodied oils, based on kerosene or mineral colza (a low-viscosity paraffinic-type oil), are extensively used for machining light alloys and for honing; at the other, heavy E.P.

oils, with viscosities up to about 100 sec. Redwood I at 140° F. are sometimes used for severe broaching operations.

Mineral oils have only slight polar properties, so their anti-friction power under boundary conditions is small. Again, although all mineral oils contain some natural sulphur, this is too firmly combined to react with the workpiece during machining, hence mineral oils have little anti-welding power. None the less, they are useful, economic cutting fluids for mild operations, and for situations in which tool life and finish are not particularly important. Although they do oxidize and form small proportions of organic acids in service, their stability is high, and they are non-corrosive in machining situations even after long service. When required, they are also usually adequate (but not invariably so, as already pointed out under *Lubricants for Machine Tools*) to lubricate the ways and slides, while small leakages into the headstock and other lubricated parts are harmless. Though any class of mineral oil is suitable, there is usually no gain from highly refined qualities, nor in adding anti-oxidants; and therefore conventional spindle oils are generally used. Typical applications are in turning and general machining of mild steel, brass and light alloys.

Fatty oils, with their strongly polar nature and high oiliness, have considerable merits as cutting fluids, but they have little anti-welding power, and as already mentioned are extremely susceptible to oxidation and thickening. Hence, although lard oil and rape oil have been extensively used, and are still occasionally met with, they have largely been displaced by compounded oils on the one hand, and by E.P. oils on the other.

Compounded cutting oils consist of mineral oil blended with up to about 30 per cent of fatty oil, which may be lard oil, sperm oil, tallow oil, rape oil and so on. Essentially, compounded cutting oils are cheaper, more stable alternatives to neat fatty oils, which they closely resemble in cutting performance. Blending with mineral oil permits the production of ranges of oils of different viscosities.

E.P. cutting oils are mineral oils containing Extreme Pressure additives, the nature of whose action has already been discussed. Their importance has increased with the severity of cutting operations and the toughness of the metals requiring machining. Sulphurized, chlorinated, and sulphochlorinated types are all in common use.

The two main types of sulphurized cutting oil are sulphurized mineral oils and sulphurized fatty mineral oils. Sulphurized mineral oils are made by the addition of elemental sulphur to mineral oil.

At quite low temperatures, such as 60° C., naphthenic oils dissolve about 0·5 per cent sulphur, but at temperatures of the order of 200° C., as much as two or more per cent of sulphur is taken up in a lightly combined form, giving a dark-coloured product with strong E.P. properties. Both these types of sulphurized mineral oil are used as cheap E.P. grades.

Another way of adding sulphur is as a sulphurized fatty oil. Fatty oils can take up large percentages of sulphur; for example, three typical commercial products contain respectively 8, 10 and 15 per cent of sulphur, and to produce cutting oils they are added to mineral oils in amounts from about 1 to 15 per cent. By careful processing, sulphur can be combined almost completely with fatty oils, leaving only negligible amounts in the uncombined, or free, condition. The state of combination is broken down by heat so that, in machining, sulphur is released at the point of cutting to react locally with the metal of the workpiece. Provided there is negligible free sulphur in the additive there is no room temperature staining of copper or other yellow metals, and hence this type is generally called an "inactive" oil (not an entirely happy term, since the oil does in fact operate by a sulphiding action).

Instead of adding the sulphurized fatty oil to a plain mineral oil it may be added either to a mineral oil containing dissolved sulphur or to a fully sulphurized mineral oil. The former method produces oils that, although darker than the mineral oil, are far from black, and are also transparent; the latter, because of the black colour of the heavily sulphurized mineral oil, produces black or near-black oils. Both types, because of the free sulphur present, usually stain copper in the cold, and therefore in the special sense of the term given above are "active" oils. "Active" oils, which are intrinsically more powerful than "inactive" oils, are particularly suitable for use in machining steels but would stain yellow metals, where, however, their powerful cutting properties are in any case not required. The black oils as a class are the more powerful of the two "active" types, but they have limited advantages over the best modern transparent qualities, which are generally the more popular, being pleasanter to handle, and allowing a better sight of the work.

As their free sulphur gives the active oils more powerful E.P. properties than the inactive, so their sulphurized fatty oil gives them better "oiliness" than sulphurized mineral oils, to which they are therefore preferred for obtaining good finish and maximum tool life. The use of a sulphurized mineral oil, a cheaper product, is in general confined to relatively crude operations such as pipe threading.

The other main class of E.P. cutting oil is the sulphochlorinated oil which, as the name implies, contains both sulphur and chlorine. These two elements may be combined in one additive, such as a sulphochlorinated fatty oil, or separate sulphurized and chlorinated additives may be used. As with the sulphurized oils, ranges of oils of different E.P. additive content are produced to suit various applications, and other modifications, such as extra fatty material, may also be incorporated. Though not so widely used as sulphurized oils, sulphochlorinated oils often prove valuable, their province particularly being that of severe operations on tough materials such as stainless steel.

Chlorinated E.P. cutting oils, containing no added sulphur, and normally consisting of blends of mineral oil with chlorinated wax, are less common than the previous types, and are chiefly used for mild to moderately severe machining. They are applicable on all types of metal, ferrous and non-ferrous, and have the attractive feature of being lighter-coloured and sweeter-smelling than sulphurized and sulphochlorinated oils. The chlorine content is usually from about 1 to 5 per cent.

Chlorinated solvents such as carbon tetrachloride and trichlorethylene contain very high proportions of chlorine and are consequently extremely effective E.P. cutting fluids, either used alone or blended into oils. However, their extremely high toxicity renders them dangerous under machining conditions, and they must therefore be used with circumspection, if at all.

Though uncommon as yet, cutting oils containing phosphorus as an E.P. element, often along with sulphur and chlorine, are in use to a limited extent, and such oils, which can be made with attractive combinations of cutting power, colour, and viscosity, may have a wider future. The additives involved are organic compounds, often very complex, containing phosphorus.

Application. For most purposes cutting oils are supplied to the point of cutting in large volume at low pressure. The rate of flow through the nozzle to the workpiece varies from about 3 to 10 gallons per minute, depending on the job. In the ordinary way, the jet of fluid flows downwards on to the job, but considerable evidence exists that a second jet directed into the clearance crevice can increase tool life, and systems of this kind are sometimes used. Where machines have their own sumps, the total volume of cutting fluid varies from some 20 to 150 gallons, but centralized systems supplying groups of machine tools are common in large machine shops. Whatever system is used, a plentiful supply to the points of cutting is essential to prevent overheating and fuming. Losses per day on workpieces and chips, and by volatilization and splashing, may be as high as 10 per cent.

The normal method of circulation is by a small gear or centrifugal pump, which draws the fluid from a sump below the machine bed and delivers it to the point of cutting. From here it falls to a collecting tray, and then flows back to the sump. Gauze filters and perforated plates in the circuit hold back the larger metal particles with which the fluid becomes contaminated.

For further details, see later, on *Handling and Care of Lubricants.*

Selection. With so many classes of cutting fluid available, selection of the best grade presents some difficulties, but suppliers of the oils provide guidance, which can be followed up by trials. Reference may also be made to a general chart originally drawn up by a Special Committee of the American Society of Mechanical Engineers, which ranges the machining operations in order of severity, and the metals in order of machinability, suitable types of cutting fluid being indicated for each combination.

Because of the configuration of the workpiece and the tool, pressures differ from spot to spot, and lubrication conditions in the cutting zone are therefore not uniform. The severest pressure is on the face of the tool, where the chip presses; nearer the tip, and below the cutting edge, pressures are less. In machining tough materials, such as steel, E.P. action is necessary to prevent excessive wear on the tool face but is superfluous elsewhere, boundary lubricants being adequate. On more easily machinable metals, pressures may nowhere demand E.P. oils. Thus not only do requirements vary from job to job, but even in one job the cutting fluid needs to cope with more than one state of lubrication.

Some features of various important machining operations may now be noted. Broaching is a severe operation, using highly expensive tools on which wear must be kept to a minimum. For broaching tough ferrous materials, therefore, powerful E.P. oils are necessary, but for softer steels and non-ferrous metals soluble oil emulsions are often used. Tapping, threading, and gear cutting are also severe operations, in which long tool life and high surface finish are vital, and E.P. oils are therefore usual. Drilling and reaming are usually less severe; emulsions are used on the easier materials, and E.P. oils on the more difficult. Milling and boring are largely done with emulsions, but in modern high-speed deep-boring machines powerful E.P. oils become essential. For turning, not usually a severe operation, emulsions are often satisfactory, but straight oils of all kinds are also used to get desired results in surface finish. Emulsions or water-base fluids are nearly universal for plain and cylindrical grinding, though straight oils are sometimes used for good finish. Powerful E.P. oils, however, are usual for thread grinding, which the heavy depth of cut makes a severe operation.

Some special cases should be noted. Emulsions are rarely used on automatics because of the dangers of corrosion and of mechanical damage from leakage into the lubricant systems of these complicated and expensive machines. Aqueous-type fluids are avoided with magnesium, because the metal reacts with water, with the liberation of hydrogen, which increases the fire risk. Dry machining, or the use of very low viscosity oils such as kerosene, is therefore the usual practice. Dry machining is also frequent with metals such as brass and cast iron which tend to form discontinuous chips.

Evaluation. Numerous instruments are available for measuring the frictional and Extreme Pressure properties of lubricants, but, valuable though these are in their sphere, none so far available correlates with the performance of cutting oils in actual machining operations. Indeed, no single test can be expected to provide such correlation, because the order of merit of cutting oils varies from operation to operation, as illustrated by the following figures obtained, in reaming, then tapping, a certain type of mild steel component.

Cutting Fluid	*Components per Tool Regrind*	
	Reaming	*Tapping*
Sulphurized Oil	1,800	21,000
E.P. Soluble Oil (15 per cent Emulsion)	3,100	1,600
Opaque Soluble Oil (15 per cent Emulsion)	700	Not tested

In the severe operation of tapping, where anti-welding requirements predominate over cooling requirements, the sulphurized cutting oil is outstanding and, in view of the much poorer results with the E.P. soluble oil, there was no point in testing the conventional opaque soluble oil. In reaming, a much milder operation, cooling becomes correspondingly more important, and the sulphurized cutting oil no longer predominates. However, cooling is not all-important because, if so, the conventional soluble oil would be as good as the E.P. soluble oil, and better than the sulphurized oil. The interrelation of cooling and lubrication requirements in this way largely explains many seeming anomalies in cutting-oil performance. Sometimes maximum tool life is the aim, sometimes good surface finish, sometimes high machining speed, and these criteria are often contradictory.

For accurate evaluation of cutting oils, therefore, actual machining tests are at present the only available method. The most common test is by drilling, but turning, tapping and threading tests are also quite extensively used. Even under laboratory conditions, extremely careful control of every factor is essential to attain reasonable repeatability and reproducibility of the results. Information from such tests can be valuable in the selection of grades for service and in developing new grades. Machining operations and working conditions vary so much, however, that actual field trials under rigidly controlled conditions are often also necessary. Laborious comparisons of various grades for a particular service are often undertaken in large machine shops where the best oil, even if its superiority is only marginal, can lead to very large economies.

Health Aspects. The odour of cutting oils, particularly of sulphurized varieties, occasionally causes slight discomfort in poorly ventilated workshops, but nothing more. On the other hand, dermatitic effects can be troublesome. Mineral oil, if allowed to remain on sensitive skins, may cause oil acne, characterized by blackheads and septic pimples. When the outer skin is broken in this way, or perhaps by cuts and abrasions, inlets are provided for bacteria which, though cutting oils as supplied are completely sterile, are inevitably picked up in use, and which can survive in oil. Cutting oils may thus carry infection into the open wound, and bacterial dermatitis may be set up, more particularly on hands and arms, but sometimes on other parts of the body. These dangers can be avoided provided that operatives follow simple precautions* as to handling cutting oils, as to clothing, and as to washing, and provided also that the machine tools and cutting oils are periodically cleaned and sterilized.

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* *Memorandum on the Prevention of Industrial Dermatitis with special reference to the use of Barrier Substances.* (Factory Dept., Ministry of Labour and National Service: Form 330, March 1946.)

HANDLING AND CARE OF LUBRICANTS

Lubricating Oils. Even the best lubricants may not perform satisfactorily if badly handled and incorrectly applied, and attention should therefore always be paid to manufacturer's instructions on these points. Storage of the oil under cover is desirable where possible, and where not, certain precautions are necessary. If stored vertically drums should be upside down, with the bungs at the bottom; in any case bungs must be kept away from water, as changes of temperature make even sound bungs "breathe" and so admit water, always an undesirable contaminant. In bulk-storage tanks, water and dust almost inevitably enter and accumulate as sludge, to remove which drain-cocks are advisable. Extremes of temperature either up or down should be avoided.

Lubricators need careful attention. Wick feed oilers depend on a combination of capillary and siphon action, and if the wick is not inserted far enough, or the oil level is too low, the lubricator ceases to function. If the end of the wick touches the shaft it may char, which impairs the oil flow, as does ramming the wick too tightly into the feed pipe. Mechanical force-feed lubricators need regular maintenance in accordance with maker's instructions. Bath oiling systems should be cleaned and flushed at intervals with light spindle oil. In gearboxes with bath systems, the gear when stationary should be immersed to a depth about equal to the tooth height.

Maintenance instructions are usually provided by the manufacturers of oil circulation systems, but if modifications are made the following points are important. Copper components should be avoided because copper strongly catalyses the oxidation of oil. Where iron and steel cannot be used, brass or bronze is preferable to copper. Zinc is attacked by used oil to form zinc soaps, and galvanized components should therefore be avoided. Oil should be drawn from near the bottom of the tank, but above the level to which sludge and water may rise. The return discharge should be near to, but never above, the surface, as the latter leads to air entrainment and foaming. Where strainers, filters and centrifuges are in the system, they should be regularly serviced according to the maker's instructions. Properly cared for, oil in large systems lasts for years, but oil that has been in protracted service should never be topped up with over 10 per cent of new oil, as oxidation sludge products soluble in the old oil may be precipitated. Complete replacement by new oil should be in accordance with the manufacturer's instructions or, in large systems, as indicated by regular laboratory examination.

There are many types of oil filter, and only passing mention can be made of some of the most important. Magnetic filters are very effective for removing ferrous particles. Purely mechanical filtration can be effected through fine gauze strainers, or through edge-type filters, in which the filtering unit consists of stacks of metal or paper discs kept apart by separators, the fineness of filtration being determined by the distance of separation. For removing water and fine suspended insoluble oxidation products, centrifuging or filtration through waste, felt, or kieselguhr is widely employed. Even dissolved impurities, such as oil-soluble oxidation products, can be removed by filtration through activated earth or clay, or charcoal, which adsorb them. Unfortunately, the various additives present in special oils are also often liable to adsorption, and such filters must therefore be used on a carefully considered basis if oil performance is not to suffer.

Greases. Grease requires even more careful handling than oil. Cleanliness is important and avoidance of high temperatures vital, as most greases are ruined by excessive heat. Hence a grease that is too stiff must not be softened by heat, but replaced by a softer grade. Grease cups and nipples should be kept in good condition and scrupulously clean. Centralized grease pressure systems must be maintained in accordance with the manufacturer's instructions. Grease-lubricated ball and roller bearings are normally packed with grease by the maker, but need periodical repacking, for which they should first be cleaned with a volatile petroleum solvent, followed by a light oil. The bearing should then be completely filled by hand, but the housing only one-half to two-thirds filled, as overfilling may cause overheating through churning. Newly packed bearings often heat up rapidly at first, but should adjust to a normal level when the grease packing has settled down. If high temperatures persist, this is possibly due to overpacking.

Cutting Oils. In mixing soluble oils, the oil should be added slowly to the water (never the other way, as this may give a water-in-oil emulsion) with continuous stirring. The water should be cool, as hot water, and even more so steam, is liable to upset the stability of the oil. Where the water is very hard (say, over 40 English degrees), previous softening may be advisable, and can be effected by adding about ¼ oz. of washing soda (hydrated sodium carbonate) per gallon. The precipitate is allowed to settle, and the supernatant clear water used for making the emulsion.

In spite of some loss of water by evaporation, the oil content of emulsions in service normally falls, because oil is carried away preferentially on chips and workpieces. To determine how much neat oil to add to restore the concentration, the oil content of the emulsion is determined by adding hydrochloric acid to a measured volume of emulsion in a graduated flask. The acid "breaks" the emulsion and the separated oil rises to the surface, where its volume can be read off, and the concentration thus determined. From this, and the volume of the system, the necessary addition of neat oil is found.*

The design of some machine tools is such as may occasion excessive splashing and foaming of the emulsion. To avoid this, the return pipe should enter the sump tank below the surface of the emulsion. Reducing the emulsion concentration also helps to minimize foaming. Avoidance of splashing, and fitting of baffles, helps fine particles to settle out, which is desirable for obtaining good surface finish. As with oil, galvanized components should be avoided, as emulsions also tend to attack zinc.

Rancid deposits sometimes form in cutting-oil systems, or the oil may develop an unpleasant odour, probably due to bacterial decomposition. In such cases the oil should be removed and the system cleaned out and sterilized by circulating a 5 per cent solution of caustic soda, followed by clean water.

The swarf picked up by cutting oils has a bad effect on surface finish, and may also help to cause skin trouble. In centralized systems, serving a number of machines, the oil is often filtered as it circulates. Where each machine has its own system, the heavier swarf is taken out by a strainer, and for finer ferrous material a magnetic filter may be included in the system. Alternatively the oil may be periodically removed and either transferred to settling tanks, in which the foreign matter settles and from which clean oil is taken from the top, or centrifuged. It is also desirable to sterilize the oil, and for this a temperature of 140–180° F., for a period of 25 to 60 minutes, is commonly recommended.

The chips formed in machining carry away considerable volumes of cutting fluid. Recovery of emulsions is rarely attempted, being uneconomic, but with oil-base cutting fluids considerable economies can be effected by breaking up the chips in chip-crushers and feeding them into centrifugal oil extractors. The separated oil may then be led to a pasteurizer for sterilization, and returned as required to the machines. Where other equipment is not available, the oily swarf may be piled on to inclined trays, down which the oil runs into containers.

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* Institute of Petroleum: *Standard Methods for Testing Petroleum and its Products* (I.P. 137/55): "Soluble Cutting Oil, Oil Content of Dispersions."

PROPERTIES OF LUBRICATING OILS

Reference has been made in the foregoing pages to various important properties of lubricating oils. Brief explanations of the terms used are given below.*

Flash Point and Fire Point—The flash point is the temperature at which an oil first gives off inflammable vapour when heated under prescribed conditions. In the Pensky Martens method, which is the one normally used in the U.K., the oil is heated at a specific rate in a lidded metal cup with a sliding shutter, which is opened every 5° F. to admit a flame. The lowest temperature at which the oil "flashes" into a transient flame is the "closed flash point." Open flash points, which are determined in the same way without the lid on the cup, are about 20–50° F. higher than the corresponding closed flash points. The fire point is the lowest temperature at which the oil in the lidless cup burns for five seconds, and is about 30–70° F. above the open flash point.

In the U.S.A., the Cleveland apparatus is generally used. In this, the cup is open and only the open flash point and the fire point are determined.

The value of the flash point depends almost entirely on the most volatile constituent present, however small in amount. For instance, a small amount of kerosene in a lubricating oil drops the flash point almost to that of kerosene alone. Flash points, especially closed flash points, are therefore useful for detecting volatile contaminants. Flash points and fire points also sometimes help to classify and identify oils.

Viscosity—Viscosity is that property of a fluid to which it owes its resistance to shear or flow. Fundamentally defined, it is the force required to shear a layer of fluid of unit thickness at unit velocity.

Accurate determination of absolute viscosities involves measuring the rate of flow in capillary tubes in special instruments. For commercial purposes, simpler instruments, in which rate of flow through standard-sized holes is measured, are used. These are: in the U.K. the Redwood, in America the Saybolt, and in Europe the Engler instruments respectively. The Redwood and Saybolt systems express the viscosity as the time in seconds for a standard volume of oil to flow through the hole. The Engler viscosity is the ratio of the time of flow of the oil to that of water at 20° C., and is expressed as "Degrees Engler". The various systems use different standard temperatures, as follows:

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* For particulars on how to make the various tests, see *Standard Methods of Testing Petroleum and its Products*, issued by the Institute of Petroleum, 26 Portland Place, London, W.1.

Saybolt Universal (S.U.)	100° F.	130° F.	210° F.
Redwood I (Red. I)	70° F.	140° F.	212° F.
°Engler (E)	20° C.	50° C.	100° C.

The viscosity range covered by various classes of lubricating oil is indicated in the following table. The limits given are of course only generalizations, to which there are occasional exceptions, such as some modern light I.C. engine oils with viscosities as low as 50 sec. Redwood I at 140° F.

	Sec. Red. I at 70° *F.*	140° *F.*	*Sec. S.U. at* 100° *F.*	°*E at* 20° *C.*	50° *C.*
Spindle Oils	75/350	40/60	55/150	2·5/11·5	1·6/2·7
Light Machine Oils	350/800	60/95	150/300	11·5/28·0	2·7/5·0
I.C. Engine Oils & Heavy Machine Oils	800/9000	95/450	300/2200	28·0/330·0	5·0/27·0
Steam Cylinder Oils	—	550/1600		—	30·0/90·0

In absolute, as distinct from commercial, units, viscosity is expressed either as dynamic viscosity or kinematic viscosity. The Absolute Dynamic Viscosity of a fluid is the tangential force on unit area of either of two parallel planes, having the fluid between them, and moving at unit relative velocity. The Absolute Kinematic Viscosity is obtained by dividing the absolute dynamic viscosity by the density of the fluid. The C.G.S. unit of absolute dynamic viscosity is the poise (p.), and the related unit of absolute kinematic viscosity is the stokes (s.). Thus: s. = p./density. Except for very viscous liquids, it is more convenient in practice to use units one hundred times smaller, the centipoise (cp.) and centistokes (cs.).

As the multiplicity of commercial viscosity systems is a nuisance, and as kinematic viscometers, though not so convenient as the commercial types, are much more sensitive and consistent, there is nowadays a growing tendency to make use of kinematic viscosities.

Viscosity Curve—Curves relating the temperature and viscosity of oils are called viscosity/temperature curves, or simply viscosity curves. When plotted on special logarithmic types of chart they are straight lines for most oils from approximately 10° F. above the pour point, up to 250° F. Straight-line viscosity/temperature charts are widely used to ascertain viscosities at temperatures other than the standard ones at which viscosity determinations are normally made.

Viscosity Index (*V.I.*)—How the viscosity of oils varies with temperature depends on the type of crude and the way it is refined. The standard scale of reference is the Viscosity Index, which indicates the slope of the viscosity/temperature curve. This entirely arbitrary scale was drawn up by selecting two types of oil, one of which—distillates from Pennsylvanian crudes—is relatively insensitive to temperature change, and the other—distillates from Gulf crudes—is very sensitive. The former was assigned a Viscosity Index of one hundred, the latter, of zero. When the viscosity/temperature curve of a particular oil is known, it is related, by an arbitrary system of calculation, to these oils. Oils with V.I.s below about 40 are called Low Viscosity Index (LVI) oils; those with V.I.s of about 40/80, Medium Viscosity Index (MVI) oils; and above 80, High Viscosity Index (HVI) oils. Most ordinary mineral oils fall between 0 and 100, but inclusion of special additives, such as polymers, can raise the figure well above 100. Again, some special lubricants, such as silicones, have V.I.s far above 100, i.e. their viscosity/temperature curves have a very gradual slope.

In most applications, high V.I. is a valuable property, as it means that the lubricant, and therefore the functioning of the machinery, is relatively insensitive to fluctuations of temperature.

Pour Point—The pour point is the lowest temperature at which an oil flows, under specified test conditions. A standard cylindrical jar containing a little of the oil is placed in a freezing mixture, and removed at every 5° F. drop in temperature of a thermometer in the oil. The temperature at which the oil just fails to flow is observed, and 5° F. above this is the Pour Point.

Acidity—Neutralization Value—Chemical changes of oils in service, by processes such as oxidation and cracking, cause rises in organic acidity, and this affords a convenient measure of the degree of deterioration. Acidity is measured as the neutralization value which is the number of milligrams of potassium hydroxide required to neutralize one gram of oil.

Saponification Value—Saponification is the conversion of fats or fatty oils into soaps by reaction with alkalis such as sodium hydroxide or potassium hydroxide. The "saponification value" is the number of milligrams of potassium hydroxide required to saponify 1 gram of an oil.

Normally the amount, if any, of saponifiable matter in straight mineral oils is negligibly small. For compounded oils, fatty oils, etc., however, the test is a valuable one.

Specific Gravity—The specific gravity of an oil is the ratio of the weights of equal volumes of the oil and water, at standard temperatures. The property is sometimes helpful in identifying types of mineral oils, which differ somewhat in specific gravity. Thus paraffinic oils as a class have specific gravities below 0·9 and naphthenic oils above 0·9.

Colour—The colour of oils is determined by comparison with standard coloured slides in a standard cell. Colour is no guide whatever to engineering performance, but is sometimes significant from other aspects, for instance in cutting oils, where light colour renders the work more visible.

Carbon Residue—There are several tests devised to evaluate the tendency of oils to form carbon in I.C. engines. In these tests, of which the best known are the Conradson and Ramsbottom tests, the oil is heated strongly out of contact with air, and the residue is weighed. Though correlation with practice is not good, such tests give a general idea of carbon-forming tendencies.

For Bibliography see end of Book.

CHAPTER XX

HEAT TREATMENT APPLIANCES

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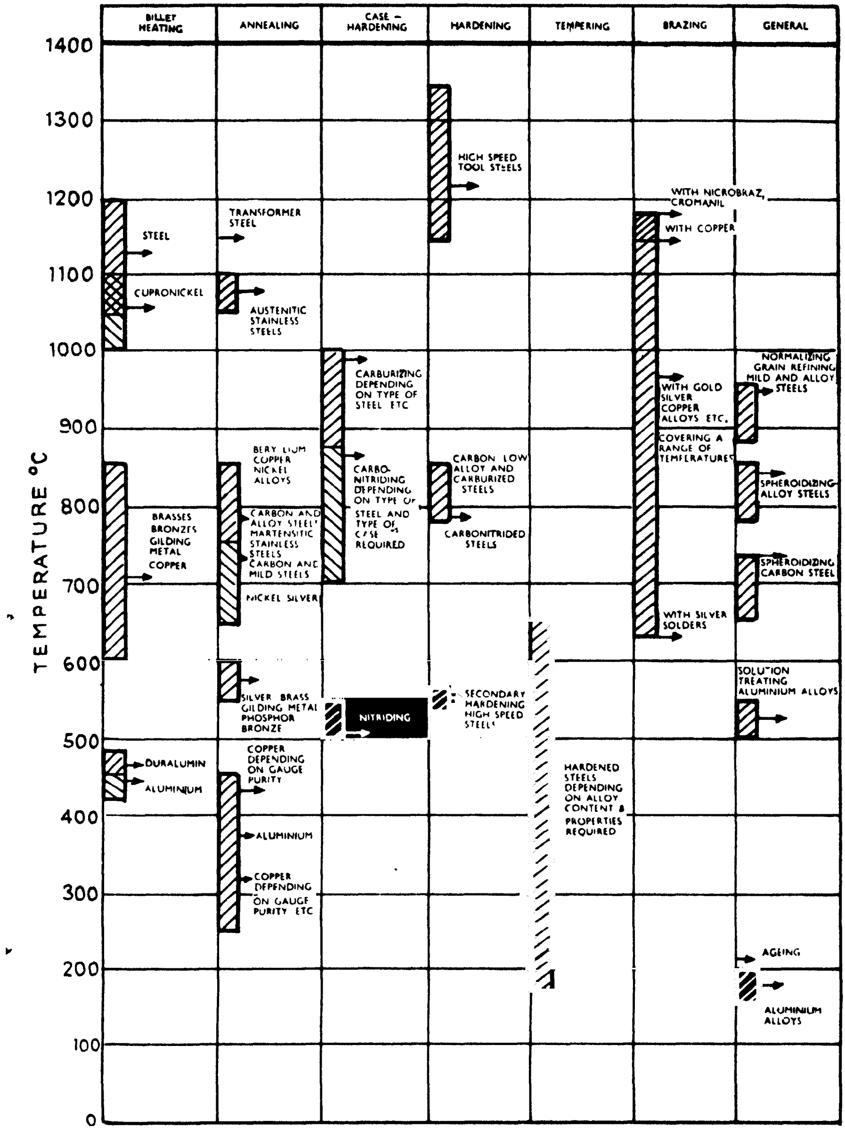
The heating and cooling of metal components under prescribed conditions aims at producing certain desirable results such as improvement in mechanical and physical properties; except in surface treatment processes (carburizing, nitriding, galvanizing, calorizing etc.), there is no change in the average composition of material. The more important factors influencing the choice of furnace are (*a*) the time cycle for heating, maintaining at a given temperature and cooling, (*b*) the mass to be treated, (*c*) the nature of the process, and (*d*) the temperature range involved. Gaseous fuel and electric power are the two main sources of heat used, but fuel oil is now often substituted for gas. It will be convenient first to outline the various general types, and then to consider which are commonly used for the successive temperature ranges. A general conspectus of these ranges is given by Fig. 20.1.

Heating Systems

GAS FURNACES may employ two main methods of firing: (i) the products of combustion of the fuel circulate about the material to be heated, while open burners are installed either in the furnace proper or outside the work-heating chamber in the path of an external fan which circulates the hot gases through the furnace; (ii) the products of combustion do not enter the work-heating chamber; muffle and radiant tube furnaces are examples of this type.

ELECTRIC FURNACES permit easy control of temperature, are suitable for use with protective-gas atmosphere, and are clean. They can be utilized in several ways: (*a*) the material to be heated serves as a resistor; (*b*) separate heating elements transfer heat to the charge by radiation and/or convection, with the heating elements either in the

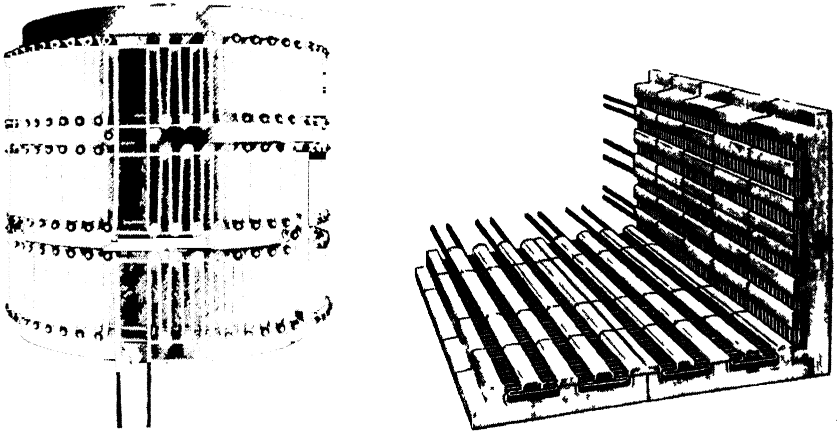


Note. Hatched areas indicate ranges of temperature

Fig. 20.1. Range of heat treatment temperatures for ferrous and non-ferrous alloys

(*Courtesy Metal Treatment and Drop Forging*) heating chamber or separated from it by a muffle wall; or (*c*) the material is heated by induction currents.

The heating elements (Fig. 20.2) may be metallic or non-metallic. If metallic they are cast, as sinuous strip, rod, coiled wire or sometimes as tube, and can be readily mounted in slots in the brickwork



Removable resistors on baffle Sinuous form Ni-Cr element

(*below*) Corrtherm element

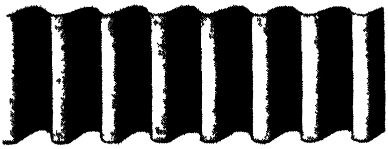


Fig. 20.2. Electrical heating elements
(*Electric Resistance Furnace Co., Ltd.*)

or suspended by pins or hooks. With the advent of gas carburizing and carbo-nitriding the electric furnace became less efficient, because of the effect of rich hydrocarbon gases on the heater material, and it became necessary to incorporate an elaborate sealed metallic muffle or retort, reducing thermal efficiency and increasing maintenance costs. The Corrtherm element, however, is unaffected by carburizing gases and no sealing baffle is therefore required. These elements are sheets of corrugated nickel-chromium alloy, hung from hooks extending from the roof and covering almost the entire walls of the furnace. The greater surface area of the element results in a lower surface temperature and therefore a longer life. Carbon deposition cannot, of course, be prevented in gas carburizing furnaces, but the voltage is so low that leakage through such deposition is impossible. Actually the oxide coating which forms on the surface of the element confines the current to the element, even when covered with soot. In addition, a high temperature enamel is fired on the element.

Silicon carbide is the most commercially important of the non-metallic resistors, which have been standardized in length and diameter. For each size, the properties of the element and the recommended thickness of the furnace wall are found in tables published by the manufacturer. When, however, silicon carbide resistors are heated above say 700° C., the carbon in the silicon carbide tends gradually to turn to carbon dioxide, whilst the silicon turns to silica, a process accelerated towards 1200° C. Hence the resistors should not be too close to the furnace wall, nor too close together.

Their resistance also increases with time, due to oxidation, so heat emission must be kept reasonably constant by use of a multiple-tap transformer, or less often, induction regulation. Normally these resistors are replaced when their resistance is doubled.

Table 20.1. Typical Rfsistors for Use with Controlled Atmospheres

Resistor Material	*Atmosphere*	*Max. Operating Temp.*
Nickel 65 Chromium 15 Iron 20	Reducing	900–950° C.
Nickel 80 Chromium 20 (improved by additions Be, Ca, Si, Ti, Zr. etc.)	Air or Oxidizing	1150° C.
Iron 72 Chromium 20 Al. 5. Co. 3	Air or Oxidizing	1350° C.
10% Rh–Pt Alloy		1600° C.
Pure Platinum		1600° C.
Molybdenum	Non-Oxidizing above 300° C.	1910° C.
Tungsten		2560° C.
Graphite		3000° C.

RADIANT TUBES. In atmospheres which are strongly carburizing and contain CO_2, severe corrosion and breakdown of the resistor material can occur, particularly at about 1000° C. Radiant tubes, of gas or electrically heated types, overcome this. The majority are fabricated from high alloy sheet metal with welded seams. Fig. 20.3 shows the construction of a modern type used e.g. in gas carburizing, vitreous enamelling and tinplate strip annealing. Some are made from silicon carbide, which limits their length: usually 4 ft. 6 in. with 6 in. internal diameter. The number and disposition of such tubes can be widely varied according to the heat requirements, and they can be replaced without shutting down the furnace.

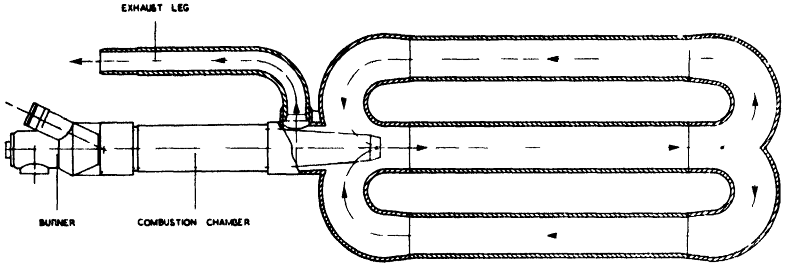


Fig. 20.3. Radiant heat element: section through " Jetube "
(*Incandescent Heat Co., Ltd.*)

INDUCTION HEATING depends on the electrical generation of heat within the material of the work-piece, which is in no way part of any closed electrical circuit. This is effected by a current-carrying conductor, called an inductor, or heating coil, which is made to surround the surface to be heated, and has the form either of a single loop, a solenoid of many turns, or any other convenient shape. The high frequency current supplied to the inductor sets up a magnetic flux in the work and magnetic fields in the area surrounding the heating coil, the strength varying inversely as the square of the distance from the coil. For maximum heating the current-carrying coil should be arranged close to the work, the average distance being $\frac{3}{32} - \frac{3}{16}$ in. when fast heating is desired, further for slower heating.

It is necessary to take into account (*a*) the power output of the generator; (*b*) the frequency of the power supply; (*c*) the design or shape of the heating coil and its relation to the surface of the work; (*d*) the resistivity of the metal being heated. The following values are only approximate, and liable to be influenced by metallurgical considerations.

Table 20.2. Induction Heating

	Optimum Value			
Frequency, C/S	3000	10,000	500,000	2,000,000
Minimum depth of hardness possible	0·060 in.	0·040 in.	0·020 in.	0·010 in.
	Practical Values			
Minimum depth of hardness expected	0·150–0·200 in.	0·100–0·150 in.	0·030–0·050 in.	0·015–0·030 in.
Minimum dia. surface hardening thin case	2 in. & over	1–3 in.	½–2 in.	¼–½ in.
Minimum dia. surface hardening deep case	2 in. & over	2 in. & over	1 in. & over	Not suitable
Minimum dia. through hardness	1 in. & over	½–2 in.	¾–¼ in.	Not suitable

(*Courtesy Electrical Development Association*)

The frequency of the power source is of great importance, since this has a direct influence on the depth of the penetration: the higher it is, up to a certain range, the more pronounced the surface heating effect. A frequency of 3000 c/s may heat a surface to a depth of 0·060 in., whereas a frequency of 500,000 c/s will produce a much shallower heat zone, of the order of 0·020 in depth. The speed at which a part can be heated and the depth of the heated layer are determined by the power output and the frequency of the generator. With proportionate power available, the speed at which heat may be applied can be made practically the same over a wide range of frequencies. For heating parts when a deep penetration is desired, frequencies of 2000–10,000 c/s are usually applied. Where only surface heating is required, 200,000 to 500,000 c/s suffices. The relation of the heating coil and the work-piece to each other determines the amount of heat transfer in proportion to the power supply.

As in a transformer, the heating coil theoretically becomes the primary and the work-piece the secondary, and, the closer the coil to the work's surface, the more intense the transfer of magnetic flux. Since high frequency heating of a metal part is the result of generating magnetic flux at the work's outer surface, and this flux decreases in intensity towards the centre, it is possible with proper timing to control the depth of heat so that, for operations such as surface hardening, a predetermined depth of case can be obtained.

The *advantages* of induction heating are: (1) comparatively low heat cost, especially with modern methods which enable only a localized surface to be heated; (2) exceptionally quick application of heat, which increases output; (3) uniformity of heating over a batch of work-pieces, with reduction or elimination of spoilage; (4) less deformation; (5) absence of scale formation; (6) facility for substitution of a higher carbon steel as a means of eliminating carburizing.

The main *disadvantage* of induction heating is the inconvenience of having to provide heat treating coils of different diameters since each different cross section requires a different coil, whether it be horizontal, vertical or inclined. Transformer taps are required for impressing the right voltage on a short section of the coil.

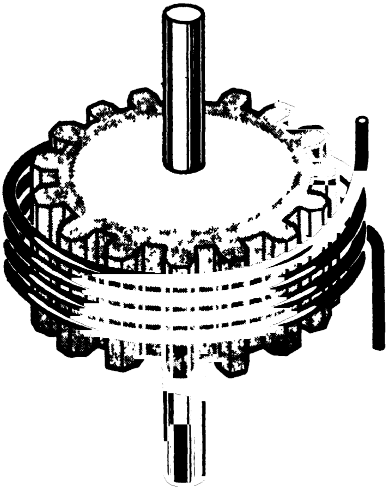


Fig. 20.4. Principle of induction hardening

A typical component being individually hardened is shown in Fig. 20.4. In this particular example there is illustrated an inductor which incorporates its own quenching device. An alternative method is to move the component to another position for quenching after the requisite heating times, dropping it automatically into the container holding quench fluid. Long objects may be fed vertically downwards through the inductor and into the quench. One of the main advantages of this method of surface hardening is the rapidity with which the process is completed, heating cycles of 5 to 12 seconds being common.

Quenching. For many purposes, air quenching is sufficient, but baths of salt or oil are also used and may be adapted for batch of continuous work. The problem of distortion arising in heat treatment has often to be met by specially designed jigs to support the work during the operation, or, more expensively (e.g. for motor-car gears) by correction in quenching presses.

FURNACES CLASSIFIED BY TEMPERATURE

Typical furnaces will be described according to progressively increasing maximum temperature of operation, i.e., (1) Low temperature ovens (up to 400° C.); (2) Medium temperature furnaces (400 to 1000° C.); (3) High temperature furnaces (1000 to 1450° C.); (4) Very high temperature furnaces (1450° C. upwards). It will be seen that some general types are used, in appropriate form at more than one of these levels.

1. Low Temperature Furnaces

VERTICAL FORCED AIR CIRCULATION FURNACE. Heat transfer at low temperatures is mainly dependent on the circulation of air in the form of convection-currents, radiation taking little part at temperatures below 500° C. A furnace on these lines (Fig. 20.5) comprises a heat-insulated cylindrical chamber with an inner concentric metal liner, or baffle, which prevents direct radiation from the elements to the charge and confines the air to a definite path. The heating elements are mounted in the annular space formed by the chamber walls and liner. The inner liner is supported in the chamber by the throat leading to the centrifugal fan at the base of the chamber. This type of furnace has a high thermal efficiency since no fresh air is drawn into the furnace and no hot air is expelled, hence the whole of the heat generated by the elements is conserved and imparted to the charge as rapidly as it can be absorbed. The temperature range is normally from room temperature to 700° C.

HORIZONTAL FORCED AIR FURNACE. This is similar in principle (Fig. 20.6). The charge is placed on horizontal open grate type shelves, their distance apart being adjustable. The work chamber may vary in size from 12 in. (width) to 16 in. (depth) × 18 in. (height) to 24 in. × 48 in. × 18 in. and the material of construction will depend on the maximum operating temperature, viz. 400 or 700° C. The ratings vary from 15 kW to 35 kW.

Such vertical or horizontal furnaces may be used for tempering such parts as aircraft and automobile engine components; gears, bolts, springs, tools, ball and roller bearings; for secondary hardening of

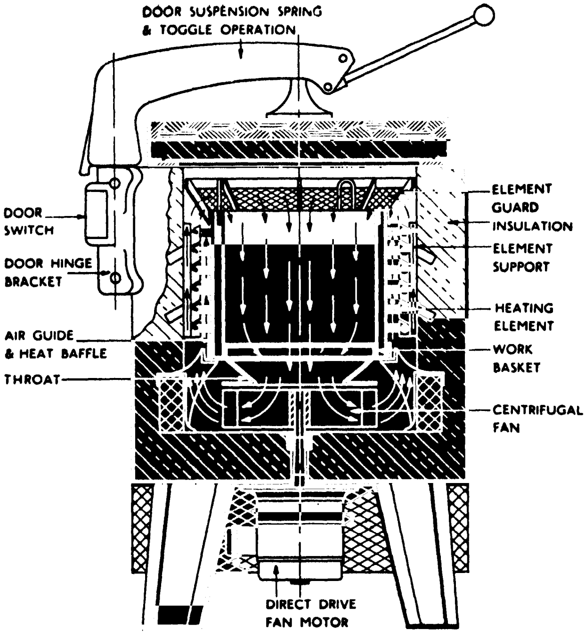


Fig. 20.5. Vertical forced air circulation furnace

(*Wild Barfield, Ltd.*)

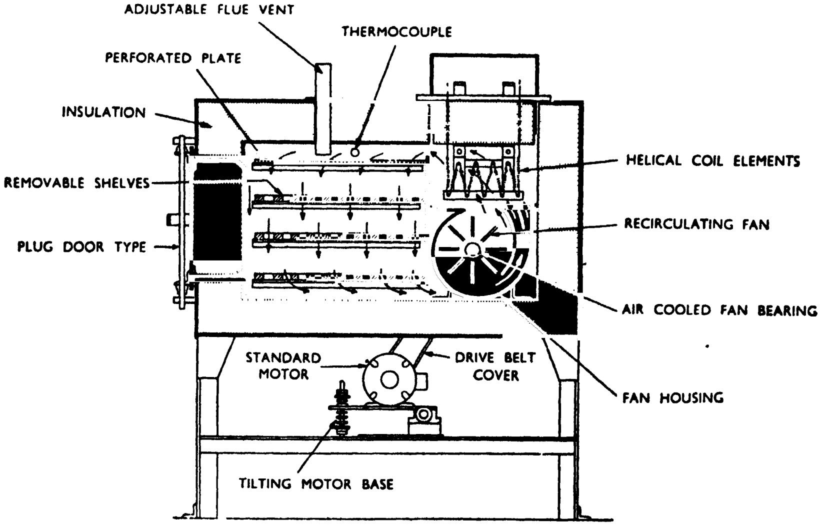


Fig. 20.6. Horizontal forced air circulation furnace

(*Electric Resistance Furnace Co., Ltd.*)

high-speed tools and cutters; for solution and precipitation treatment of aluminium and other light alloys; for annealing of non-ferrous materials, pressings, stampings or for nitriding.

Salt Bath Furnace. This is commonly heated by direct current, either externally or (more often) internally, by vertically or horizontally immersed electrodes (Fig. 20.7). This method is possible because the electrical conductivity of the salt is low compared with that of the metal or graphite electrodes. The life of the metal container is not very great; ceramic containers have a much longer life provided they are initially heated. The following points should be considered when spacing electrodes in the salt baths: (1) the conductivity of the bath varies with the composition of the salt and its temperature (this point cannot be too strongly stressed—low temperature salt baths usually contain $NaNO_3$ and this, when strongly heated, decomposes causing explosions); (2) the cross section of the electrodes; (3) the depth of immersion; (4) the voltage impressed on the electrodes.

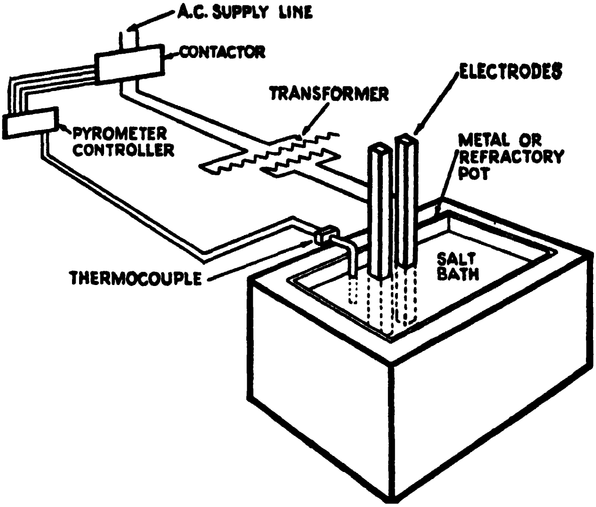


Fig. 20.7. Arrangement of electric salt bath furnace
(*Electric Resistance Furnace Co., Ltd.*)

Salt baths may also be heated by gas or radiant tubes; with the latter, the maximum temperature is about 700° C. Their use at higher temperatures is referred to below.

2. Medium Temperature Furnaces

The mechanical design of the electric resistance furnaces mostly used in this range varies very widely, but they may be broadly classified as (*a*) *Batch type* where the charge is inserted, heat treated and removed, or (*b*) *Continuous type* where the charge progresses through the heating zone. Either may utilize a controlled atmosphere to prevent scaling and decarbonization or for carburizing, carbonitriding, etc.

(A) BATCH TYPE FURNACES

The Box Furnace (Fig. 20.8) has a solid hearth of area up to 150 sq. ft.; as its name implies it is box-shaped and the work may be charged through door openings by means of tongs or a mechanical charger. It is used for annealing, normalizing, tempering, carburizing, malleableizing, vitreous enamelling etc.

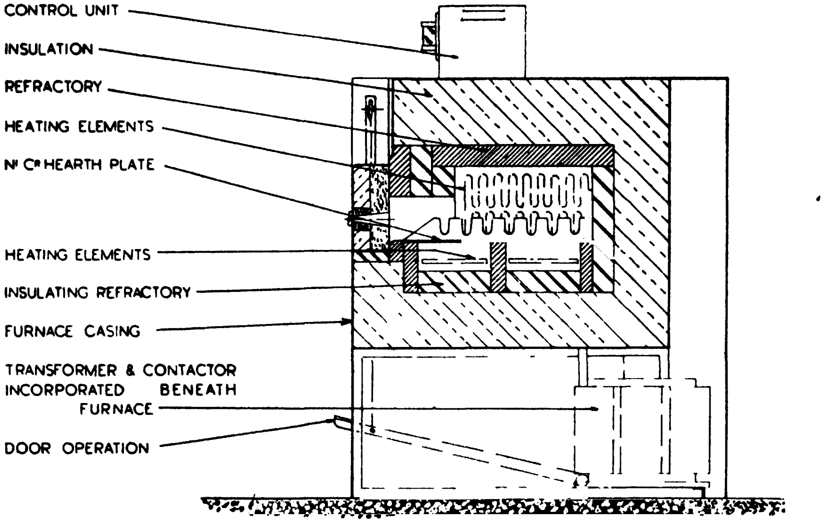


Fig. 20.8. Box furnace

(*Metalectric Furnaces Ltd.*)

The Movable Hearth or Car Bottom Furnace consists of a shell fitted with heating units, the work being supported upon a separate car, which runs in and out of it to charge and unload. For uniform heating of the work, the latter is supported on piers or heat-resisting alloy castings, which also afford clearance for chains and gripping tongs. For preventing free circulation of gases through the furnace shell, all car-type furnaces must be provided with a gas, sand or water seal. The sand seal is better since the end wall of the water container interferes with the endwise movement of the car, and also the water evaporates and increases scaling if the vapour enters the chamber. In large furnaces, these cars are too heavy to be handled manually, and have to be moved by some such device as a cable, to which they are hooked, worked by an electric motor through a set of reduction gears.

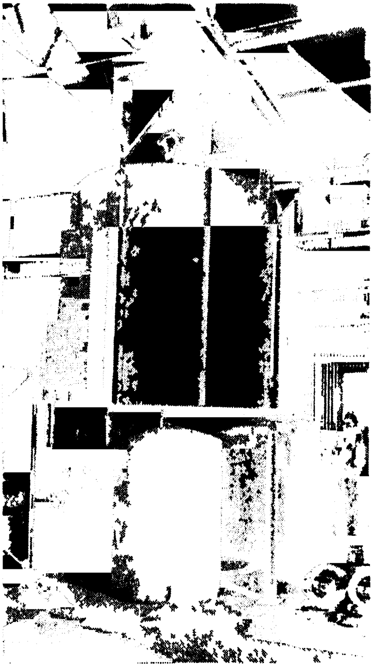


Fig. 20.9. Lowering a bell type furnace over a sealed hood

(*G E C*)

The Bell Type Furnace (Fig. 20.9) is usually cylindrical, to suit coils of strip and wire, but some are rectangular to handle stacks of sheets. They are mainly used for processing material which requires special surface protection from oxidation and decarburization, and also for annealing, and hence may be called pack annealing, coil annealing or cover annealing furnaces.

The furnace shell is removed by crane and set aside whilst the material is being stacked on a permanent base or stand. A light inner cover is placed over the stack, sealed with refractory material or low melting point alloy (e.g. Cerrobend) at the bottom, and provided with a constant supply of prepared gas atmosphere, and then the shell is lowered over the assembly. It is fitted on the inside with electrical resistance units, is lined with refractory insulation material, and braced so that it can be moved from base to base. The circulation of the gases inside the inner cover is by natural or forced convection, the fan being located in the base.

THE VERTICAL CYLINDRICAL OR PIT FURNACE. This furnace is essentially a thermally-insulated refractory-lined pit with heating elements disposed around its walls. The material is suspended by a fixture of heat resisting steel bars, or loaded into a basket, and this may be inside a container of light gauge heat-resisting steel sheet with inlet and outlet for controlled gases; the whole being lowered into the furnace. Pit furnaces are used for bright annealing of coiled ferrous and non-ferrous metals and are suitable for most controlled atmosphere processes. Containers, often more than 12 ft. deep and up to 3 ft. in diameter, will heat treat 3–4 tons of coiled wire.

THE SALT BATH FURNACE already described may be used, with suitable composition of the salt, for temperatures of 400 to 1000° C. Johnson* points out that mixtures chosen are usually of chlorides, or chloride and carbonate, such as the following.

(*a*) Potassium Chloride 50%, Sodium Carbonate 50%, max. permitted temp. 600° C. Steels undergo decarburization in this bath unless KCN or NaCN be added.

(*b*) Calcium Chloride 56%, Sodium Chloride 44%, m.p.t. 503°C. If this bath be heated above 900° C. atmospheric oxygen is absorbed causing decarburization. The remedy here is to add a rectifying agent such as fused borax or boric oxide, which combines with the oxidized products to form a sediment.

(*c*) Sodium Cyanide 20–50%, Sodium Carbonate 37–40%, Sodium Chloride 18–30%. This mixture of fused salts can be used in this temperature range, but it is more commonly known as a case hardening bath. Carburizing or case hardening, using cyanide salt baths, is very suitable for the production of shallow cases; a temperature of about 870° C. is maintained for ½–1 hr. to give a case 0·008 inches thick assuming the original material contained 0·4–0·5% carbon.

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* F. Johnson, *Metal Treatment and Heat Treatment Manual*, vol. III, 1948.

(B) CONTINUOUS TYPE FURNACES

These are used where large quantities of material of similar size and heat treatment are involved—they may be subdivided according to the way the material is moved: (*a*) cast link, chain, slat belt and mesh belt, (*b*) roller hearth, (*c*) pusher, (*d*) shaker hearth, (*e*) walking beam, (*f*) rotary hearth, (*g*) rotary drum, (*h*) draw through. They may be heated by gas, electricity or a combination of both, and may or may not utilize a controlled atmosphere.

Cast Link, Chain and Slat Belt Conveyors are used for handling miscellaneous small and medium sized parts such as nuts and bolts, rivets, bearing rings, starters, etc. Should the chain however be slightly overloaded, it will gradually elongate and its pitch will change. Chain conveyors are usually driven from the charging end and the chain strands are guided through the furnace by alloy rails and troughs; for furnaces over 30 feet long, it is often advisable to drive the chain from both ends. The method of conveying the charge will vary, sometimes the chain is provided with fixtures which project above the carrying rails in the furnace and slide and roll the

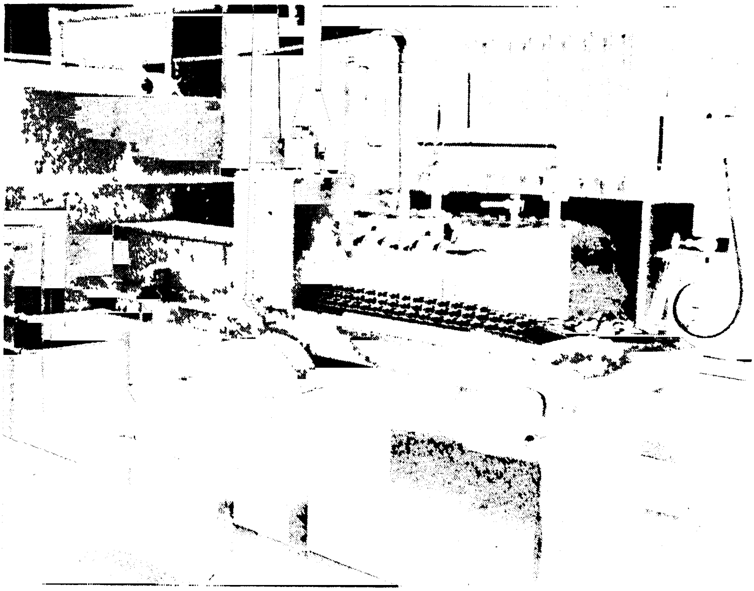

Fig. 20.10. Continuous mesh belt furnace

(*Metalelectric Furnaces Ltd.*)

charge through the furnace on these rails, or (e.g. in the automobile industry) overhead chains may be used with alloy hangers projecting through a slot in the roof. A woven wire alloy belt is used, for example, for copper brazing, at about 1150° C.; the same tendency to stretch under tension while hot can be minimized by various patented tensioning mechanisms. Fig. 20.10 shows the charging end of a mesh belt furnace for annealing mild steel pressings; an exothermic atmosphere protects the charge. Furnaces of this kind will have outputs of the following order.

Belt Width	*Rating*	*Overall Length*	*Approx. Output Bright Mild Steel at* 930° C.
6 in.	20 kW	22 ft. 9 in.	75 lb/hr.
24 in.	120 kW	49 ft. 8 in.	800 lb/hr.

ROLLER HEARTH FURNACES are especially suited for uniform treatment of large numbers of identical components, such as rod, tube, strip and bulky articles (which are loaded directly on to the rollers), wire coils, and small pieces (carried through the furnace on trays). In processes requiring atmosphere control, heating is by electric resistors or gas-fired radiant tubes. The roller hearth consists of nickel chrome chain-driven rollers with provision for varying the speed of travel. Notable advantages over the conveyor type are that there is virtually no limit to the length and that heat economy is better since the rollers are within the furnace and not constantly heated and cooled as is a conveyor.

PUSHER TYPE FURNACES are most useful for heating heavy components to forging and rolling temperatures, or bright annealing metal strip, and wire in coils. The charge, depending on size, may be placed on carrier shoes, on trays, directly on the hearth, or may be suspended from a metal channel in the roof. End discharge or gravity discharge is often arranged, so that several side by side can discharge on to a common conveyor.

SHAKER HEARTH FURNACES are particularly adapted for the continuous heat treatment of large numbers of small components, e.g. needles, knife blades, flat springs, washers, etc. The mechanism for reciprocating the hearth may be mechanical (using an electric motor) hydraulic or pneumatic. The charge is moved through the heating chambers by means of a series of small steps and discharged by means of a chute into the quenching tank below. Typical sizes and outputs are:

Hearth Width	*Rating*	*Length*	*Width*	*Output*
6 in.	12 kW	7 ft. 9 in.	3 ft. 0 in.	¼–½ cwt/hr.
18 in.	45 kW	11 ft. 9 in.	4 ft. 6 in.	1½–3 cwt/hr.

WALKING BEAM FURNACES employ a special mechanism comprising a number of long parallel sets of alloy supports, one or more being stationary. The motion to the charge is imparted by the movable beams repeatedly lifting the material upwards and forwards, depositing it further along the stationary beams and returning to their position by a downward and backward motion. This method is often used in a continuous box type sheet annealing furnace for tubes, rod, bar and other structural shapes.

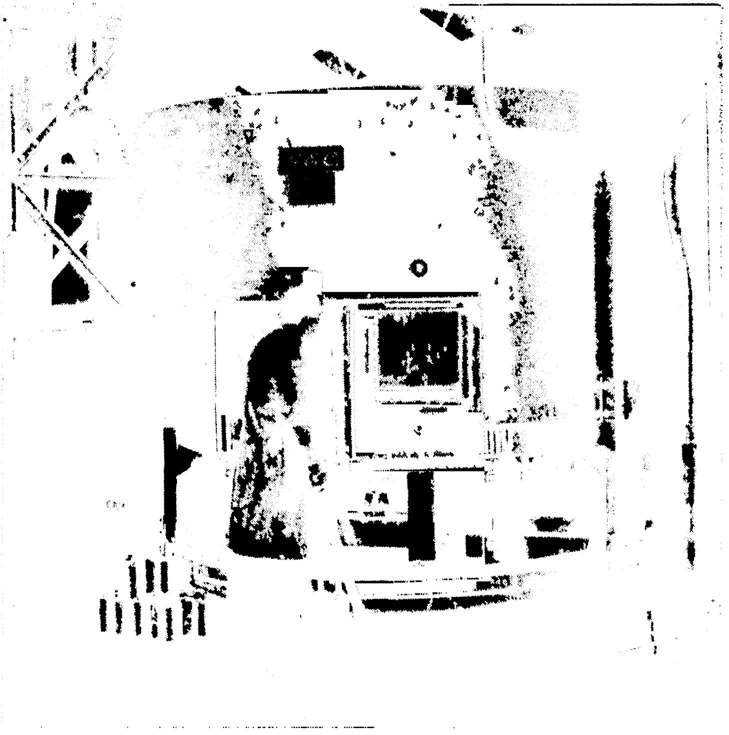

Fig. 20.11. Rotary hearth conveyor furnace

(*G.E.C.*)

ROTARY HEARTH CONVEYOR FURNACES (Fig. 20.11) are adapted to heating shapes that cannot safely be pushed through, e.g. long rounds lying on the hearth, short rounds standing vertically, plates, gear wheels, etc. They comprise a cylindrical furnace chamber with a rotating hearth, which remains inside the furnace, giving good thermal efficiency. A sand or water seal is needed; typical data are as follows:

Rating	*Hearth Width*	*Overall Length*	*Output at* 850° C.
45 kW	12 in.	8 ft. 3 in.	400 lb/hr.
120 kW	19 in.	11 ft. 4 in.	950 lb/hr.

Steel workpieces are usually supported on alloy supports above the hearth bottom, ingots and forgings placed on the hearth. As the charge and discharge doors are located side by side, only one operator is required. The rate of rotation and furnace temperature are so adjusted that the components receive the required heat treatment by the time they reach the discharge position.

ROTARY DRUM FURNACES (Fig. 20.12) are designed for light

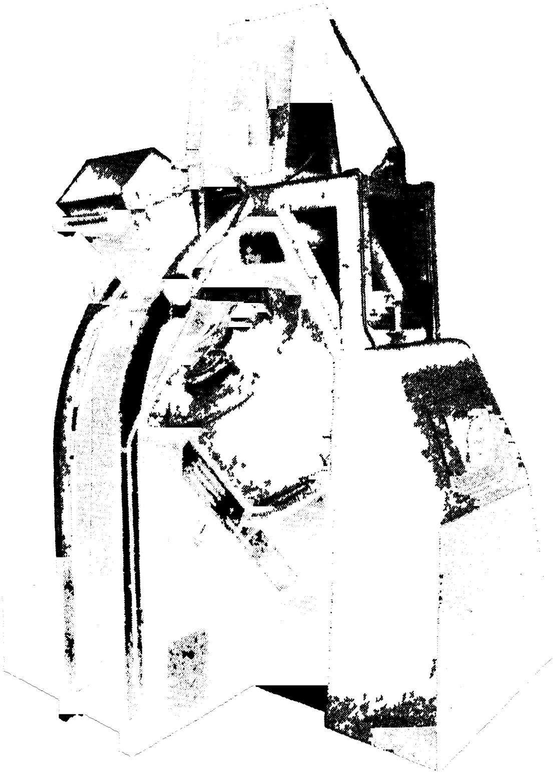

Fig. 20.12. Rotary drum furnace (*Birlec*)

charges, e.g. brass cartridge cases, which can be tumbled without damage. This type of furnace often consists of two consecutive drums with oppositely threaded spirals, which control the movement of the charge. Loading and discharge may take place at one end with the heating element at the other, the outgoing work usefully heating that coming in.

DRAW THROUGH TYPES are used for the heat treatment of wire and strip. Wire is annealed or patented in multi-tube furnaces, the spooling mechanism at the discharge end serving to draw the wire through. This type of furnace is also used for handling large quantities of strip, both ferrous and non-ferrous, with and without controlled atmosphere, an example being the heat treatment of alloy stainless strip for razor blades. The furnace may be horizontal, occupying much floor space or vertical, when it is called a tower furnace, the strip travelling up and down several times. To make the process continuous, provision is made to stitch-weld the new strip to the end of the old. Radiant tubes or resistors may supply heat in four or five units, the cooling being usually atmospheric.

3. **High Temperature Furnaces** (1000–1450° C.).

It is usual when operating at these slightly higher temperatures to preheat the article to say 600° C.

SALT BATH FURNACES are again here employed, usually with a mixture containing fluorides and chlorides.

ELECTRICAL MUFFLE TYPE FURNACES for this range typically use silicon carbide elements, fixed vertically in the side wall and extending below the level of the silicon carbide hearth plate.

To reduce scaling and decarburization of high speed steels treated in this type of furnace, atmosphere control is necessary. One type utilizes paraffin (kerosene) as the atmosphere-producing medium, fed from a container with a hand pump to a burner, or series of burners, beneath the sill bricks. Another has an inner lining of carbon black.

GAS FIRED FURNACES are commonly provided with two heating chambers, the uppermost being used in general for preheating. Both chambers are of muffle type, i.e., they are externally heated with no contact between the work contained in the chamber and the heating gases. The bottom chamber only is fired by a set of burners, the waste gases heating the top one.

4. **Very High Temperature Furnaces** (1450° **C. and upwards**).

Furnaces for these temperature ranges are frequently electrically heated. That in Fig. 20.13 has graphite elements with molybdenum radiation screens. Table 20.3 lists some metals used for elements. Hancock* mentions a completely new material made from molybdenum disilicide with a metallic bond, usable up to 1700° C., and fabricated by powder metallurgy. Carbon granules for electric heating are now being tried, in soaking pits for steel ingots, their advantage being the presence of a partially reducing atmosphere which assists in counteracting the loss due to scaling.

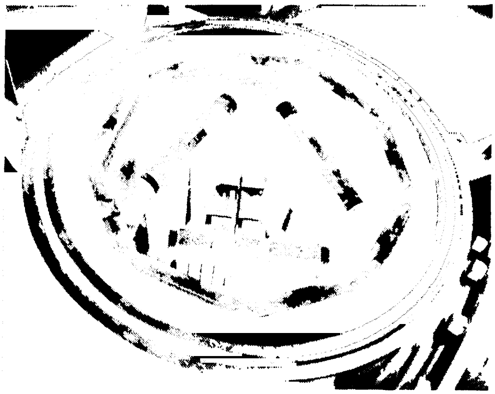

Fig. 20.13. Vacuum furnace for 1800–2500 C.
(*G.E.C.*)

TABLE 20.3. METALS FOR HIGH-TEMPERATURE ELEMENTS

Metal	*Melting Pt.* (°*C.*)	*Highest Working Temp.* (°*C.*)
Tungsten	3410	2560
Tantalum	3030	2400
Rhenium	3180	2380
Niobium	2420	2230
Molybdenum	2630	1910
Platinum	1773	1600

(*After* Kieffer and Benesovsky, *Metallurgia* (58), September 1958)

Platinum and platinum alloys are used for heating elements in laboratory furnaces, at temperatures up to 1600° C.; but owing to their high initial cost and relatively high vapour pressure, not in larger industrial furnaces.

Molybdenum in the presence of air or an oxidizing atmosphere, is oxidized, and as the oxide is volatile furnaces using molybdenum elements must either be evacuated, or purged with a stream of hydrogen or an inert gas. Molybdenum reacts with certain ceramic materials at high temperature, but if the heating element is allowed to hang freely, temperatures up to 1910° C. can be obtained. Another disadvantage of molybdenum as element material, the difficulty of contact resistance of the terminals, has been overcome by the use of water cooled copper terminals, with terminal or contact points of molybdenum or tantalum.

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* 'Electric Furnace Development' (Birmingham Metallurgical Society, 23 January 1958).

If a high vacuum is required, molybdenum is only used up to 1700° C., but tantalum up to 2200° C. The effect of temperature upon the electrical resistance of molybdenum demands the fitting of control transformers and temperature control devices.

Niobium elements could be an alternative to tantalum, but at present the cost is too high. Tungsten may be employed to 2500° C., if no contact is permitted between metal and ceramic, and a reducing or inert protective atmosphere or vacuum; such a furnace is mainly used for sintering in powder metallurgy, and the heat treatment of high melting-point metals.

For Bibliography see end of book.

CHAPTER XXI

ELEMENTS OF PRODUCTION ENGINEERING

By J. SAXBY

Production Engineer, Mirrlees, Bickerton and Day, Ltd., Stockport

A Production Engineer requires a knowledge of the basic principles of Engineering, of the separate processes involved, of the many ways in which the processes can be combined to achieve a specific objective, and of the organization required for their successful coordination. For making an ever-increasing range of products automatic and semi-automatic plants are now used, and moving conveyors and automatic handling devices employed for assembly. Firms have developed and designed their particular products to facilitate mechanized production and their production engineering staffs have developed methods and tooling equipment to achieve this economically.

The manufacture of cars, tractors, radio and similar products needed in large quantities over long periods obviously requires thorough and accurate planning beforehand. Large and well-trained staffs can be employed because the cost involved is soon recovered on the large quantities efficiently produced. Progress on similar lines has also been made in the heavier engineering industries; probably not as rapidly, but certainly faster than at any time since the Industrial Revolution. The British medium and heavy diesel engine industry for instance has undergone major changes in recent years both in design of engines and in manufacturing methods. Power-weight ratio has been increased by the use of turbo-charging and higher engine speeds, and in many cases the present methods of manufacture bear little or no resemblance to those of the past. The two main factors responsible for improvements are that cutting tools and many machine tools have changed almost beyond recognition, and that jig and fixture design, gauging equipment and handling methods have been very greatly altered to improve interchangeability, eliminate unnecessary fitting, reduce operator fatigue, and cut time and costs.

Factory Administration. The responsibility of maintaining and constantly improving these production techniques lies with the personnel of the Production Engineering section. In the past the Works Manager was personally responsible, through his assistants, superintendents and foremen for the control of every department concerned with production. But nowadays in most businesses of large size we find a Works Manager, a Plant Engineer, a Personnel Officer, a Production Engineer and a Production Controller, each directly responsible to a Works Director or Planning Director who in turn, is generally responsible to the Managing Director.

The *Works Manager* is responsible for the smooth running of the factory, for discipline, for settling disputes and claims with organized labour, and ensuring that production levels and targets are maintained.

The main duties of the *Plant Engineer* are to ensure the provision of adequate services such as heat, light, power and water, etc., to instal new and to maintain existing plant, carry out building repairs and supervise extensions etc.

The *Personnel Officer*, apart from engaging personnel, is responsible for absentee and time-keeping records; for interviewing in cases of dispute the representatives of organized labour and placing their cases and facts before the appropriate executive; and is often the company's representative on one or more of the many joint consultation committees which now exist.

The *Production Controller* is in charge of the main stores and must ensure that sufficient stocks of raw material, castings, components etc.—whether bought-out or made-on-works—are always available. He is also responsible for the preparation of assembly instructions to sub-assembly and main assembly departments.

The main duties of the *Production Engineer*, with whom we are here concerned, are to supply the factory with the necessary facilities in machine tools, jig and fixtures, gauges etc., for producing components and assembling the final product with accuracy and economy. He must have under his direct control a staff of Process or Methods Engineers, Jig and Tool Designers, Ratefixing and Work-Study personnel, and Development Engineers both for machine and assembly shops, tool room and tool stores. It is absolutely essential for success nowadays that the closest co-operation should exist between the Design and the Production Engineering Departments.

Steps to Production. When the Design Department have completed drawings of a new product or component, discussions should be held with the Process or Methods Engineer with the object of so simplifying its design as to minimize machining and assembly difficulties and to ensure adequate location points for jigs and fixtures. Failure to do this may later result in heavy production losses or retooling costs. As the drawings for each component are agreed between the design and process offices, the Process Engineer then proceeds to specify the method of manufacture, setting out in full detail every operation and sub-operation required for the completion of each part.

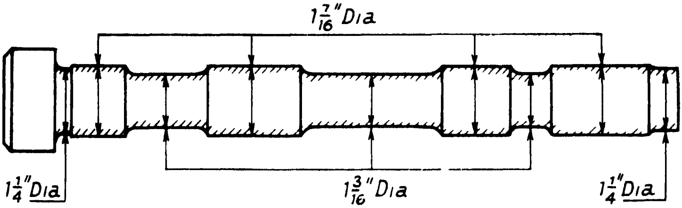

Fig. 21.1

An operation sheet for the highly stressed connecting rod bolt, Fig. 21.1, typical of many used in diesel engines, will give a sketch like that shown, and all data required for work with three machine tools: (1) A Frazer end-milling and centring machine in which two milling cutters first cut the stock bar to length and then face the ends, and centres are made at the two ends simultaneously; (2) A Fischer profile-copying lathe working from a master profile and using single-point tools; (3) A Sentinal "Cri-Dan" screwing machine with compressed-air chucking and a single point carbide tool, which makes a predetermined number of passes over the bar to reach the correct thread-depth. The instructions are clearly but concisely set out, with references by numbers to machine types, jigs or fixtures, gauges, dial settings, speeds and feeds; and the sheet also records the number required per unit per production line, the material, and such details as whether to be Lloyds tested. There is space for tool records, and where capstan or turret lathes are involved there may be a diagram showing the tool set-up.

Production time is estimated, and the Jig and Tool Department first carefully studies the component and the process lay-out, so as to ensure that their designs minimize time, manual effort and movement of the component. Costs, it is emphasized, must be kept down with simple tooling, for small quantities, but if large runs are in question, the cost of quick-action clamping or air or hydraulic devices may be justified. Duplex fixtures (Fig. 21.2) enable an operator to load one component while another is being machined and multi-spindle drills (see Chap. V) save time. Fig. 21.3 shows milling and drilling fixtures suitable for small batches. Gauges in particular must be convenient to handle and give quite unmistakable indication of the correctness

Fig. 21.2. Single-spindle boring machine with Duplex jig for boring connecting rods

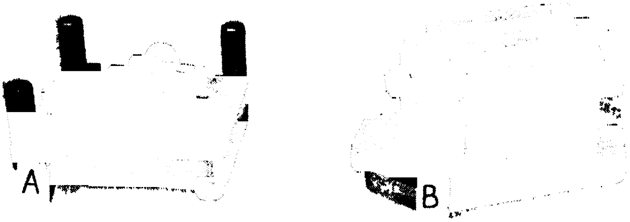

Fig. 21.3. (*A*) Simple drilling jig. (*B*) Simple milling fixture, for small batch work

or otherwise of the particular dimension; otherwise the operator will suspect their accuracy.

When the jig and tool designs have been completed and the Chief Jig and Tool Draughtsman is satisfied that the equipment will operate as planned as far as can be ascertained at that stage, manufacturing orders are placed either on an outside firm or the Tool Room. The process lay-out and a copy of the jig drawing are passed to the Ratefixing Department, when the final piecework prices are estimated ready for issue to the operator. More will be said about the function of this department later.

Immediately the incoming tooling has been accepted by Inspection, it is passed to the Tool Store where each item is recorded on some system e.g. Kardex, to facilitate easy location. Information that the tooling is ready for use is then passed to Material Control and Machine Loading section. Process drawings are sent to the works Drawing Stores ready for issue to the shops.

The Development Engineer then takes over and develops each individual operation, until all unforeseen difficulties are removed and the component reaches final inspection, stores or assembly as the case may be. Apart from this, he must see that the estimated times, laid down by the Process Engineer, can be maintained or, better still, improved upon. Otherwise, consultations are held between Process Engineers and Tool Designers to find the remedy, for, if the planned speed should not be achieved, the balance of machine capacity and production costs will be seriously impaired.

When the Development Engineer is satisfied that the job is running satisfactorily and can be handed over for full production, the Ratefixer negotiates with the operator to agree on a fixed time per component. Several methods are in operation in Great Britain, according to the local agreements with organized labour. In some cases piecework times are fixed by using a stop watch; alternatively, times can be built up from a knowledge of speeds and feeds and similar standard elements for machine manipulations, etc. which have been calculated over a period. All methods are applied, however, to provide an incentive for the operator, maintain standard costs, and improve productivity.

Tool Stores. When the jigs and tools are no longer required in the machine shop they are returned to the main tool store, which is the nerve centre of any machine shop. Different factories have varying systems, but a new factory just setting up could not go far wrong by employing the principles in tool stores organization here indicated.

The main tool store should be situated centrally to eliminate unnecessary walking. Within the general store is a smaller "bonded store" which holds new and unused tools required to replenish its floating stock. This only applies of course to consumable tools such as drills, taps, milling cutters, reamers, dies and grinding wheels, etc. The bonded store is controlled on a maximum and minimum stock basis, determined by the usage over a period, and the Chief Storekeeper is responsible for ordering equipment to maintain these stocks. A stock control card can usefully provide for recordings the supply (with alternatives) the purpose, the weekly and monthly usage, the quantities in which ordered, the minimum and maximum stock, the current price paid, the location by bin and row, the orders placed and delivered, and then the several issues: number, to what operator, and leaving what balance.

Outside, in the main tool store, jigs and fixtures complete with their ancillary equipment such as bushes, drills, reamers, cutters, etc. are stored as complete kits in bins, preferably of timber, which is less likely to cause damage to the valuable equipment. They should be marked with a reference number to provide quick location from the record index card, and this card should give dates of issue of the tool layout, dates of return to stores and details of any repairs carried out.

When a batch of components is to be sent to the shop for early machining, the shop-loading section notify the tool store personnel who can then arrange to have the complete tool kit for that particular operation assembled in readiness.

On completion of the job the tool layouts are returned to the tool store, but before being replaced in the racks they are thoroughly examined. Drills bushes are checked for size, location faces inspected for wear or indentations, cutting tools are reground and everything put in first class order.

Tool Grinding. The tool grinding section must clearly work closely with the tool stores, the ideal arrangement being their combination under one foreman. It is then possible to ensure that all tools, lathe tools, drills and milling cutters, whether special or standard, are reground by operators with a sound knowledge of cutting angles, rakes and clearances, thus removing from the operator the responsibility for regrinding his own tools.

An efficient tool grinding section for a large factory needs various types of grinding machines. First there must be universal cutter-grinding machines suitable for grinding the flutes and lands of reamers, sharpening taps and grinding shell and side-and-face milling cutters. They must be fully equipped with attachments for indexing, holding work between centres or in universal vices, and, where numerous form tools are in use radiusing and profile-forming.

If the factory makes extensive use of large diameter face-milling cutters on horizontal or vertical machines, or on plano-milling machines, it becomes necessary to instal special machines such as the Edgwick or Walther face-mill grinding machines which are available with capacities up to 42 in. diameter. A good quality machine is essential as it is most important, especially with tungsten carbide cutters, that each cutting blade should be ground to the same distance from the spindle mounting face; otherwise some of the blades will have to remove more than their share of stock and thus will become more subject to failure.

No person, however skilful, can ensure that a drill ground by freehand methods will be accurate. In a factory where large numbers of drill are used, especially if three and four flute in addition to the normal two flute type, one of the automatic types of drill-grinding machines is strongly recommended.

In addition to these more specialized machines, there should be ample provision for the regrinding of lathe tools, for shank roughing and tip roughing, and a diamond lapping machine for finishing the tips.

Fig. 21.4 shows a section of a tool store and cutter grinding department organized along these lines and with a number of the grinding machines which have been described.

A proper tool preparation system, especially where carbides are in wide use, can in a large factory result in considerable economies, as different machine operators have various theories on rakes and cutting angles which can result in broken tools or uneconomical grinding, whereas central grinding enables them to get replacements immediately from standard stock.

Forward Planning. The Chief Production Engineer of any organization should always be thinking several steps ahead of present requirements, and, using sales department statistics as a guide, planning the future development and possible extension of the factory. This involves two specific exercises, first the actual planning of the factory layout to facilitate flow production and second, in factories with budgetary control, the necessary budgets for expenditure on machine tools and other capital equipment.

For planning factory layout there are several well-tried methods:

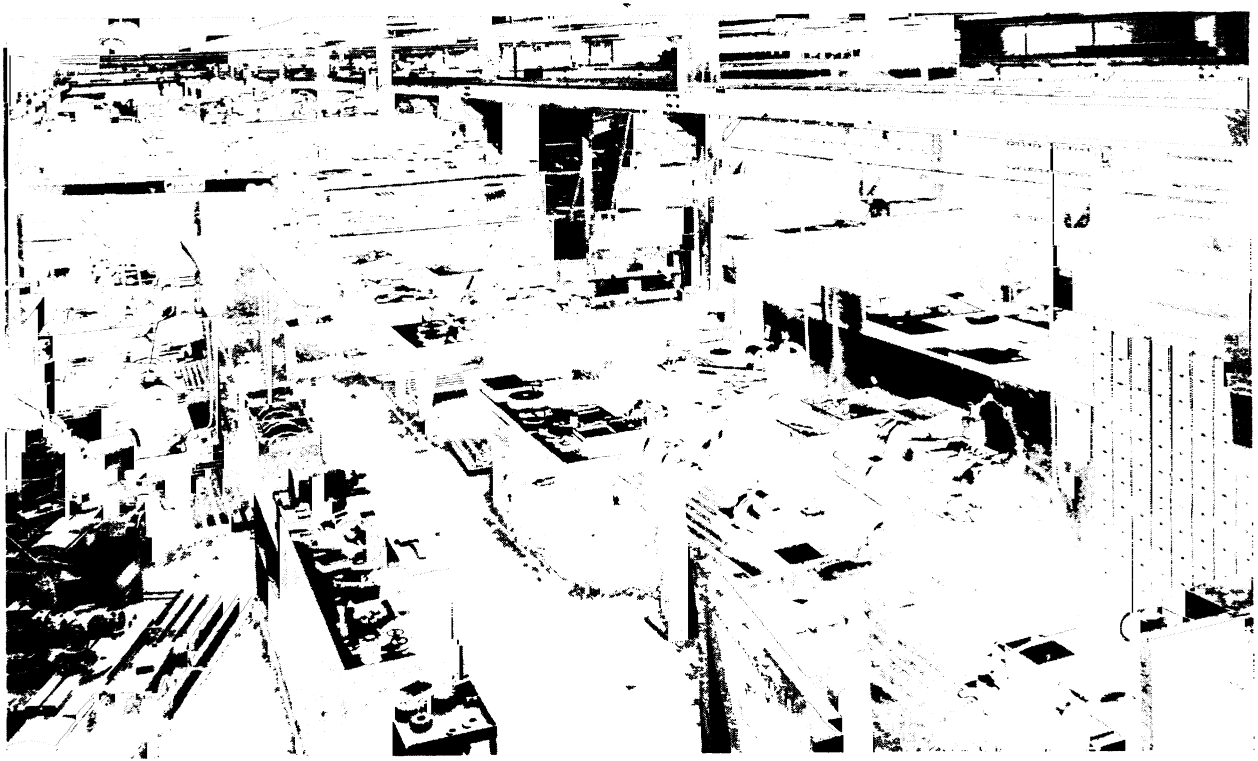

Fig. 21.4. A general view of a section of a tool stores, showing on the left the tool and cutter grinding section, in the centre the jig inspection and in the right-hand background the jig and tool storage racks

(*a*) To make a conventional plan drawing; (*b*) To use cardboard cut-out models pinned to an outline drawing of the building; (*c*) To use three-dimensional scale models. Of these, (*b*) is probably the most convenient and most frequently adopted. It has the advantage that alternative schemes can be simply illustrated by moving the cut-outs to new positions, without any redrawing. Further, by connecting a piece of thread to pins in the machine-models concerned with a particular component and measuring its final length one can find the distance that workpiece travels through the factory.

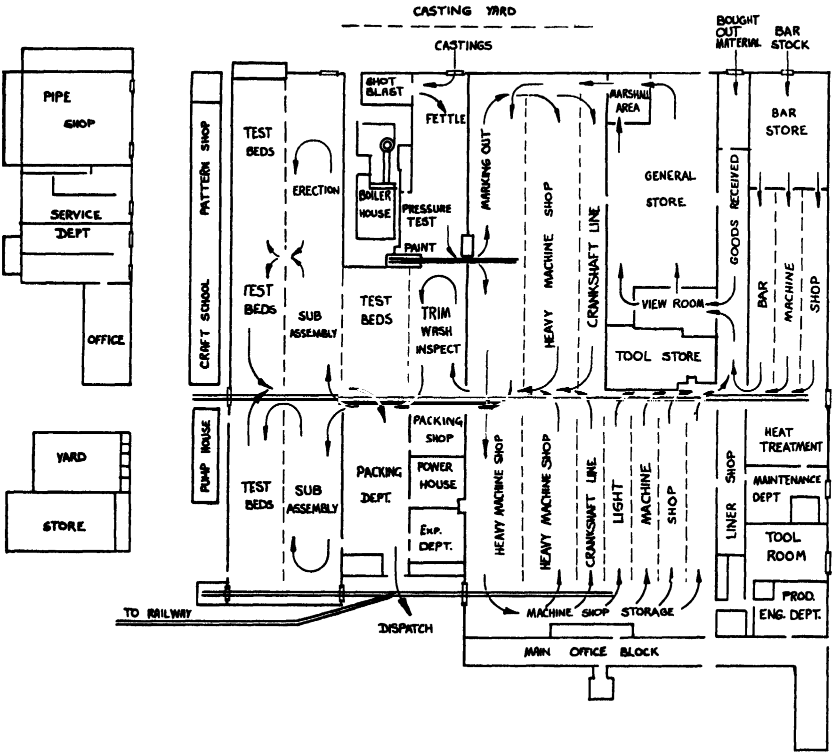

Fig. 21.5. Layout and flow diagram of a modern factory

Close attention should be paid to the gangways in the shops to permit free passage of vehicles, such as fork-lift trucks, and ample space should be left around the machines for work in progress.

The factory of which Fig. 21.5 is the layout consisted, some years ago, of several separate buildings which were of identical span and construction, but due to the fact that each building was a separate unit it was found impracticable to introduce flow production. Over the past few years, however, this factory has expanded considerably and with careful planning these separate buildings have been incorporated into the main building resulting in a factory which is almost square and ideal for systematic layout. The raw materials and bought finished items are delivered to a goods receiving department at one side of the factory, and the former progress through the various machine shops until they finally converge on the inspection view room and stores. From stores they then flow through sub-assembly, main assembly and test to packing and despatch at the far side of the factory. A good idea can be obtained from this plan of the relative proportions, and positions in the factory, of the tool room, tool stores and cutter grinding departments.

Materials Handling. In the heavier engineering industries where much of the work is too heavy for an operator to lift repeatedly, individual means of lifting should be given full consideration. Overhead gantry cranes are of course a necessity for the really heavy lifts for large planing machines, etc., but where a large number of machines have to be served with one or two overhead cranes, much time can be wasted through machine operators having to wait for it. In such cases, and also for medium sized components, (say of ½ cwt

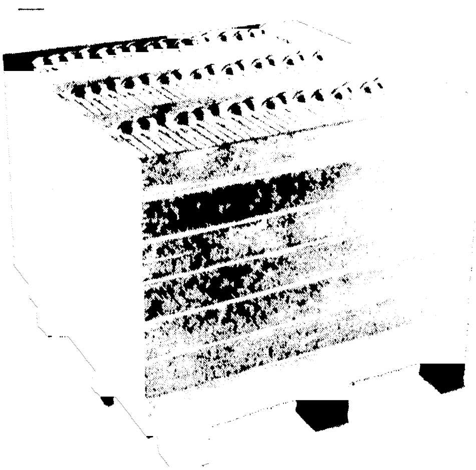

Fig. 21.6. Special containers for storage and transport of valves, to prevent damage to stems and seatings

to 1 ton) individual jibs or monorails can prove a valuable factor in eliminating waiting time and fatigue. Where a production line of machines is served by jibs, the areas covered by them must slightly overlap to permit the work to be transferred from one machine to the next.

None but the very largest components should ever be transported loose; for all unnecessary handling adds to the cost of the component but nothing to its value. Wherever possible the work should be transported and stored on either pallets or stackable metal box containers which can be obtained in various standard sizes. It may be desirable with certain components to provide special pallets and containers to prevent accidental damage (Fig. 21.6). Wherever possible rider-controlled power vehicles, such as fork-lift trucks and stillage trucks, should be used for the movement of work from point to point in the factory; short-wave radio provides an efficient means of controlling these vehicles and ensuring that wherever possible they carry payloads in both directions.

Budgeting. One of the major annual duties of a Production Engineer, made necessary by the close financial control required nowadays, is the preparation of budgets for capital expenditure on new plant for factory reorganization and the day-to-day revenue expenditure on consumable tools, etc. It is here that the Production Engineer's knowledge of machine tools is perhaps most important. If a company is preparing to spend one or two hundred thousand pounds on machine tools, it must be absolutely sure that the machinery will fulfil the duties expected of it and that it is of sound design and good construction and needs the minimum of maintenance. The Production Engineer will need to submit to his Managing Director and Board an absolutely concrete case for the purchase of any new plant, hence accurate records must be kept of the actual load in hours per week or month for all machines, so that additional capacity, if required, may be quickly authorized. Records should also be kept, but by the maintenance department, of any machines which, through age or excessive work, are costing large sums in maintenance or are otherwise unsatisfactory. Replacements of such equipment should be covered in the annual budgets; it is easy to arrive at an accurate estimate, as in all cases quotations will be required from the machine tool supplier. Contrasted with this, the costs of factory reorganization can usually be estimated only approximately, after agreement between the Production and Works Engineers, from the previously prepared plans and drawings.

Assembly and Work Study. The duties of a Production Engineer do not finish when the final machining has been carried out, as the components must then pass to the assembly lines for building up into the finished product. It is here that the Assembly-processing and Work-Study people take over. First the assembly processer studies the standard specification, issued by the design office, and from this breaks down the product into a number of assemblies or sub-assemblies which can be carried out prior to final erection. For diesel engines for instance, these sub-assemblies are usually cylinder heads and valve gear, governors, piston conn-rod and large end units, and control panels, etc. Lists of all components required for these sub-assemblies are prepared and the sequence of assembly is determined, the lists, or copies, being then passed to material control and stores who prepare the material for issue to the fitting shops. The Work-Study people then check the issue list against the sub-assembly to ensure that everything is complete and that the subsequent work-study will not fail due to shortages of components.

During the assembly of the components the work-study man notes anything in the layout of the workplace which may cause unnecessary handling, reaching or searching; any awkward bit of assembly which could be simplified by the provision of a holding fixture, special spanner or other piece of equipment; or any item best transferred to another assembly. The information gathered is passed back to the assembly processer who makes any necessary amendments to his assembly lists and process sheets, and requisitions any special equipment required. The work-study people finally agree with the fitters upon a piecework time for the assembly and these times are recorded on the appropriate documents.

Sometimes the method or work-study engineer and the fitter or fitters concerned may not agree on the piecework time offered for the job, it is then most important that the method-study engineer should have a good practical background, to avoid any attempt by the operator to exaggerate the work involved and thus obtain more time for the job than is strictly fair.

A good method-study engineer can often advise how to simplify a difficult job by some suitable equipment. For instance, the insertion of a 2½ in. B.S.F. stud into a diesel engine cylinder casing previously had to be done by two fitters pulling on a six-foot spanner, as it was outside the capacity of any available power tool. Now however, with a 3:1 gear-reduction unit and a medium sized power impact wrench the fitting of these studs is quite a simple operation for one man, thus halving the labour cost and eliminating fatigue. (Fig. 21.7.)

The efforts of the work-study men can also be utilized to great benefit in the machine shop. For instance, the large numbers of highly stressed studs which had to be manufactured from sawn blanks of high tensile steel, seemed to demand an additional power saw and operator in the bar stores. The outcome of careful work-study however was the manufacture of a multiple bar-holding fixture complete with chain and pinion traverse motion to feed the bars up to the cutting stop. This, designed to accommodate seven bars for

Fig. 21.7. The 3.1 reduction unit and impact wrench for inserting 2½ in. B.S.F. studs

sawing at once, in varying sized cradles, has proved so successful that, sawing times have been reduced by 40 per cent and the need for an additional saw and operator eliminated. (Fig. 21.8.)

Sometimes components may not assemble correctly and then the Development Engineer must investigate the troubles, find out what is wrong and initiate any modifications which are required in design.

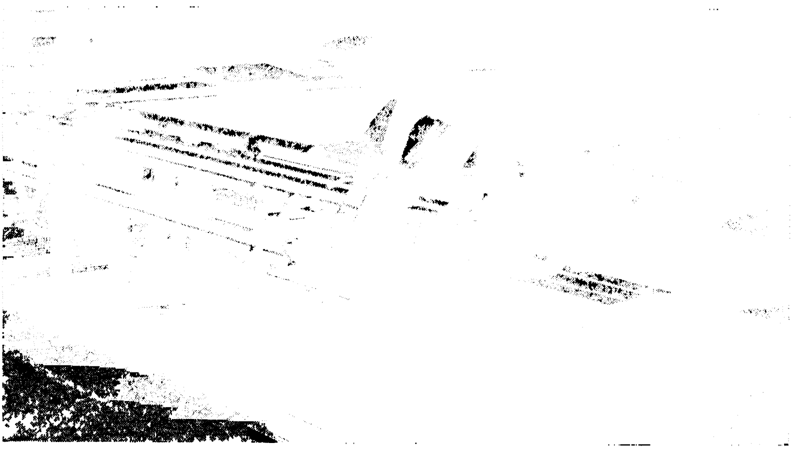

Fig. 21.8. Multiple bar cutting attachment as applied to a standard Wicksteed saw

The Tool Room. While nowadays many firms putting a new product on the market prefer to have most of their jigs and tools manufactured by one or the other of the specialist firms, it is still necessary to maintain a well-equipped tool room to cope with the repair of jigs and tools and to manufacture any which there is not time to buy. It must have the best possible machine tools, and all machine operators and fitters must be first-class craftsmen as much of their work demands the highest skill, as in the production of master profile formers, templates and gauges, etc. Normally, apart from a jig boring machine and sometimes a die-sinking machine, the machine tools required are of a standard nature such as precision centre lathes, grinders and milling machines, but due to the great variety of work they must be well equipped with the numerous attachments for taper turning and grinding, indexing, dividing cam-milling and profile, etc.

Importance of Adaptability. The best laid plans will not prevent the occurrence of unforeseen problems and the Production Engineer must always be prepared for the emergency recasting of process layouts, speeds and feeds, tooling schedules, piecework times and the like. An instance from practice will not come amiss. Close grained cylinder liners, 15 in. bore and some 3 ft. long, were turned and rough bored on a specially tooled-up Herbert 9B/30 Combination Lathe. The excessive overhang of the large diameter boring bar required the incorporation of a sliding pilot bar down the centre, located in a bush in the machine spindle nose. But the large amount of cast iron dust which settled on the pilot bar (though wipers were fitted) and on other sliding surfaces penetrated into the bearings and caused repeated seizures. Furthermore, the intense heat generated by the tools during a large number of combined boring and turning operations caused the loosening of the carbide tool-tip due to the heat melting the brazed joint. Numerous types of wiper, such as copper, felt, rubber and neoprene were tried unsuccessfully, while vain efforts were made with a dust extraction unit. The final solution was reached when, against all the usual principles in the machining of cast iron, it was decided to try a soluble coolant. Besides curing the two troubles previously mentioned, this prolonged the cutting tool life, kept the liner at a lower temperature, (therefore enabling more accurate measurements to be taken), and considerably improved the working conditions for the operator.

Keeping Up to Date. It is a duty of the Production Engineer to keep abreast of machine and cutting developments so that he can always choose the best available plant. This he does by reading the professional journals, the manufacturers' technical publications and the current books, and by seeing the generally very knowledgeable representatives of the machine tool firms, who can often suggest solutions to problems in the light of what has been done elsewhere. Exhibitions, both at home and abroad, are invaluable opportunities of seeing the latest plant and exchanging ideas, and most big firms find it well worth while to provide facilities for attending them.

Cooperation in the Factory. In many up-to-date factories today the approach of management to labour has changed out of all recognition in recent years and many of the old barriers of prejudice have been broken down. This relationship varies according to the nature of the business but invariably top management and top union officials meet regularly for frank discussions of day-to-day problems, labour development of the company, the order book and many other issues domestic or otherwise which may effect the smooth running of the concern. The conference with which the Production Engineer is mainly concerned will typically deal with such topics as the development of equipment, flow of material, services, etc. Usually the Chairman will be a high ranking executive or Director, taking as far as he can an unprejudiced view. Representation of the department may consist of the Works Convenor, departmental stewards and two or three reliable operatives, together with the Superintendent, Foreman and Chargehand concerned; of the management, the Production Engineer with some of his staff, such as Chief Jig and Tool Draughtsman, Chief Process Engineer and possibly Chief Ratefixer, depending on the items on the agenda. The Works Manager also would attend, and any other executive from say, Design or Production Control could be called in if required. Generally at such a meeting the feeling of the department can be measured, and the reaction e.g. to the introduction of quicker methods ascertained, before resentment or misunderstading ruin a well-intended scheme into which money and energy have been poured.

The greatest reward a Production Engineer can have is to witness the successful application of a machine or a jig, or even the opening of an entirely new department, containing many of his own and his staff's ideas, perhaps after months of hard work. But the personnel of the section concerned must be equally enthusiastic if complete satisfaction is to be realized.

Production Engineering as a Career. Because the Production Engineer's duties lie between the management and workers, the position demands a man of great drive and vigour and one who is somewhat of a sportsman, capable of taking hard knocks but still keeping cheerful.

This profession is comparatively young, and only now are the Technical Colleges providing adequate facilities for training. The decision to become a Production Engineer should be taken early to enable the student to acquire a very wide practical knowledge of the plant in his own factory, and the machines in general. He must be conversant with cutting speeds and feeds for drilling, milling, turning, grinding and planing; must have practical knowledge of the life of cutting tools generally, and be in a position to formulate methods which may be used with the plant he has at his disposal. While the practical experience is being gained, particular care should be paid to the methods of holding workpieces during machining, to ensure accuracy and freedom from distortion. It may also be necessary to have similarly detailed knowledge of such processes as welding, heat treatment, etc.

For a man of the right type prepared to acquire the academic knowledge and the quite equally important practical experience of machines, tooling and men, there must be few other occupations which offer the same scope and interest.

For Bibliography see end of book.

CHAPTER XXII

PRINCIPLES OF STANDARDIZATION

By DR. F. KOENIGSBERGER

It is well known that the manufacturing cost of a product is the lower the greater the quantity required. If a great number of parts are produced in a batch the cost of the highly specialized tooling which is essential for most efficient production adds little to the cost of the single item. On the other hand, the cost of small quantities, and particularly of a "one off" part is usually rather high, as such overheads as the cost of drawing-office work and of any special jigs and tools have to be carried by the small number of components or the single item produced. This, in turn, does not allow the use of elaborate tooling and, therefore, increases manufacturing times and reduces production efficiency. The standardization of parts used in small quantities for different applications and in different industries enables manufacturers who specialize in the manufacture of such parts to produce them in larger batches than would otherwise be possible.

Whilst a standardization of time, of money and of weights and measures has long existed in various countries, the beginnings of standardization in engineering date back only to the middle of the nineteenth century. The most common element of machinery, the screw thread, was standardized by Sir Joseph Whitworth in 1841 and was followed by the standardization of material specifications, wire and sheet metal sizes, rolled sections, keys, screws and nuts, rivets, etc.

It has often been stated that standardization cramps the style of a designer, but the fact that the opposite is the case is being more and more appreciated. Standardization enables the designer to concentrate on the real design problems without having to waste time on those which have been solved by others or which are more efficiently dealt with by specialists in a particular field. Where would machine design and construction be if, e.g. each designer had to design, and each factory to manufacture, its own ball bearings?

The term standardization is commonly applied to materials, parts or mechanisms. A very important application, however, is in the use of standard dimensions and other numerical values, as standardization can very considerably reduce design work and tooling and manufacturing cost. The standardization of material specifications covering composition, mechanical properties, size and shape, results in a simplification of purchasing, testing, inspection and storage procedures. Together with the standardization of limits and fits, the standardization of diameters and tapers leads to a reduction in the necessary stocks of such tools as drills, reamers, plug and snap gauges. The standardization of radii in machined items and castings reduces the required number of profile tools for machining operations and blending tools used by pattern makers. The standardization of machine tool spindle speeds and of gear reduction ratios (see Chap. I) helps not only to simplify the designer's work but also to facilitate and to speed up production planning and progressing.

The purpose of standardization is, therefore, on the one hand efficiency and economy in the use of human time and effort, and on the other hand economy of material varieties and stock quantities, and, therefore, reduction of capital outlay and increase of turnover.

Standardization can be divided into:

(1) Basic Standardization: Preferred numbers, preferred sizes, scales and weights, voltages, air pressure in factory pipe lines, screw thread profiles, limits and fits, surface texture, testing procedures, drawing and writing paper sizes, etc., in other words, standardization of items which are applied in all fields of industrial life.

(2) Dimensional Standardization of engineering components: Screws, nuts, rivets, dowels, keys, gear tooth pitches, etc.

(3) Material Standardization: This may be applied to types and qualities, sizes and shapes of materials used for the manufacture of various products, as well as to tools, lubricants and other consumable goods.

The first group is based on general considerations of numerical theories. An example is the use of geometrical progressions for preferred numbers with ratios based on $\sqrt[5]{10}$, $\sqrt[10]{10}$, $\sqrt[20]{10}$, $\sqrt[40]{10}$, (see Chap. I). Another example is the metric standardization of paper sizes in which the length to width ratios are $\sqrt{2}$. This results not only in the same length to width ratio of the various sizes, but also in the sizes of sheets folded in half, quarters, etc. being identical. It also makes possible the photo-copying of all sizes on the same film sizes and printing papers and greatly assists filing.

Groups two and three really represent the result of suitable selection from the full range of approved quantities and qualities such as the International Standards in which every theoretically justified and practically suitable item is represented. An example is the I.S.O. standard of limits and fits which covers every conceivable tolerance and allows for any possible combination of allowances and tolerances.

From this large group national standards are selected for those items which are considered essential and suitable from the point of view of the industrial and economic requirements of each particular country, and from the national standardization the selection can proceed to even smaller and less varied groupings in different industries or other ways of life. Thus standardization need not even be limited to parts in common use in all fields of engineering. Groups of industries or even single firms can find great advantages in introducing their own standards if and when required.

As an example of group standardization Fig. 22.1 shows some standard parts used in the machine tool industry, manufactured by a few firms specializing on these lines and produced by them in

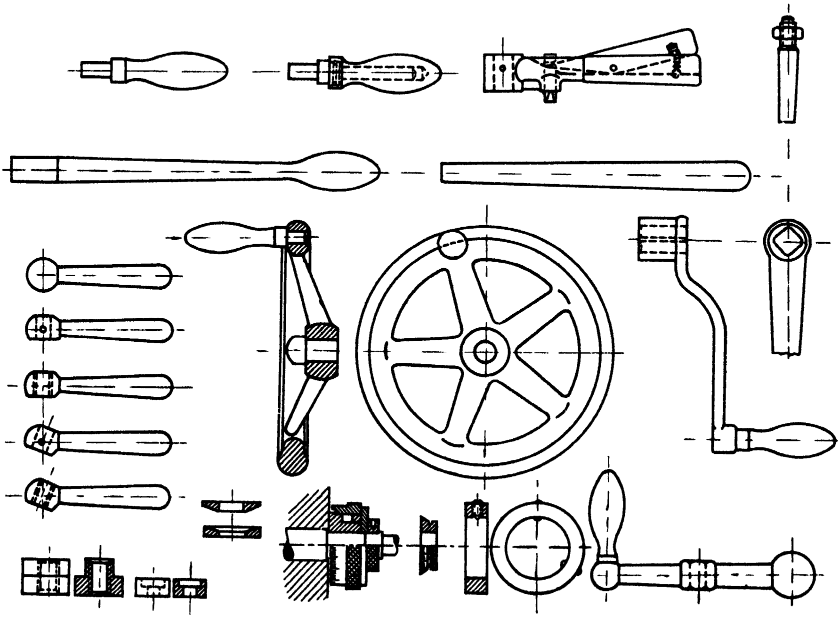

Fig. 22.1. Standard parts used in the machine tool industry

sufficient sizes and quantities to cater for the needs of machine tool makers in a particular country or even all over the world.

Fig. 22.2* is an illustration of design standardization within one factory and shows how a firm producing horizontal boring machines standardized complete assembly units for their range of machines.

In Table 22. 1 some British Standards for screws and bolts, and in Table 22.2 some rolled plate sizes supplied by rolling mills are compared with corresponding works standards used in a large manufacturing organization.

TABLE 22. 1

SCREWS AND BOLTS			
B.A. THREADS		*WHITWORTH THREADS*	
British Standards	*Works Standards*	*British Standards*	*Works Standards*
0	0	$\frac{1}{4}$	$\frac{1}{4}$
1		$\frac{5}{16}$	$\frac{5}{16}$
2	2	$\frac{3}{8}$	$\frac{3}{8}$
3		$\frac{7}{16}$	
4	4	$\frac{1}{2}$	$\frac{1}{2}$
5		$\frac{9}{16}$	
6	6	$\frac{5}{8}$	$\frac{5}{8}$
7		$\frac{3}{4}$	$\frac{3}{4}$
8	8	$\frac{7}{8}$	$\frac{7}{8}$
9		1	1
10	10	$1\frac{1}{8}$	$1\frac{1}{8}$
11		$1\frac{1}{4}$	$1\frac{1}{4}$
12	12	$1\frac{3}{8}$*	
13		$1\frac{1}{2}$	$1\frac{1}{2}$
14	14	$1\frac{5}{8}$*	
15		$1\frac{3}{4}$	$1\frac{3}{4}$
16	16	2	2
17		$2\frac{1}{4}$	
18		$2\frac{1}{2}$	
19		$2\frac{3}{4}$	
20		3	
21		$3\frac{1}{4}$*	
22		$3\frac{1}{2}$	
23		$3\frac{3}{4}$*	
24		4	
25		$4\frac{1}{2}$	
		5	
		$5\frac{1}{2}$	
		6	

*To be dispensed with wherever possible.

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* From C. A. SPARKES, " Machine Tool Simplification as Applied to Horizontal Boring Machines," *Proc. I. Mech.E.*, **166**, (1952), 450.

TABLE 2.

MILD STEEL PLATES

THICKNESS IN.		*WIDTH IN.*		*LENGTH IN.*	
Rolling Mills	*Works Standards*	*Rolling Mills*	*Works Standards*	*Rolling Mills*	*Works Standards*
		(*Max.*)		(*Max.*)	
3/16	3/16	72	48 72	360	96 120
1/4	1/4	90	48 72	420	96 120
5/16	5/16	96	48 84	480	96 144
3/8	3/8	100	48 96	780	96 144
7/16	7/16	105	96	780	144
1/2	1/2	108	48 96	780	96 144
9/16		108		780	
5/8	5/8	108	48 96	780	96 144
11/16		108		780	
3/4	3/4	108	48 96	780	96 144
13/16		108		780	
7/8	7/8	108	48 96	780	96 144
15/16		108		780	
1	1	108	48 96	780	96 144
1 1/8	1 1/8	108	48 96	780	96 144

TABLE 22. 2—*contd.*

MILD STEEL PLATES

THICKNESS IN		*WIDTH IN.*		*LENGTH IN*	
Rolling Mills	*Works Standards*	*Rolling Mills*	*Works Standards*	*Rolling Mills*	*Works Standards*
		(*Max*)		(*Max*)	
1¼	1¼	108	48 96	780	96 144
1⅜	1⅜	108	48 96	780	96 144
1½	1½	108	48 96	720	96 144
1⅝		108		720	
1¾	1¾	108	48 96	720	96 144
1⅞		108		600	
2	2	108	48 96	600	96 144
2¼	2¼	106	48 96	480	96 144
2½	2½	106	48 96	480	96 144
2¾	2¾	106	48 96	480	96 144
3	3	106	48 96	480	96 144

For Bibliography see end of book.

CHAPTER XXIII

SAFETY DEVICES

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General Requirements. The "fencing" or "safeguarding" of all dangerous moving parts incorporated in a prime mover, or in transmission or production machinery is definitely required by the Factory Acts and by certain regulations made thereunder which apply to particular kinds of hazardous machinery. These should be consulted for particulars of current legislation and for definitions of the various parts that are required to be protected (often in specified ways). It must be remembered that not only must the machine attendant or operative be safeguarded, but also every other person employed or working in the factory. Suitable and existing methods and devices for the fencing of transmission and other machinery are described and illustrated in various pamphlets and leaflets issued by the Factory Department of the Ministry of Labour and National Service, while information on views and safety practices in the United States of America have been published by H. W. Heinrich (see list of references).

A number of decisions upon the interpretation of the fencing requirements of the Factory Acts have been given over a long period by the Divisional Court, the Court of Appeal and the House of Lords, also by the Scottish High Court of Judiciary which necessarily influence the legal standards to be adopted, of which the following are of importance.

The guard for any dangerous parts must be of the *best type* known to be existing in the whole country, not merely that in the best factory in any given locality, so that before any particular guard is fitted, inquiries should be made as to the existence and use of a better one. H.M. Inspectors of Factories will be able to give assistance, and the Factory Department continues to publish from time to time illustrations of guards and safety devices for the more common accident-producing machines.

In assessing danger from working at any machine, no account should be taken of personal characteristics such as carelessness, the neglect of instructions as to safe working, dull-wittedness; in fact, as the law stands, every workman has an absolute right to the fullest protection from dangerous machinery. Machines that are not included in any code of regulations are subject to the case of Davies *v.* Thomas Owen & Co. Ltd., 1919, in that if a machine cannot be fenced securely while remaining commercially practicable or mechanically useful, the Statute, in effect, prohibits its use, so that some other and safe machine must be used instead.

The Factory Acts place the general responsibility upon the occupier of a factory for safeguarding machinery, except in the case of certain specified parts for which the maker or seller of the machine is responsible. But legal requirements, while they must be observed, do not usually state in definite terms the practical means wherewith compliance can be given to them and it is within the province of the Safety Engineer to supply that information.

Intrinsically Dangerous Mechanisms. Hitherto precise information has not been available as to those parts which should definitely be guarded wherever they exist. Unless such information is known, machinery will continue to be designed, manufactured and used which will inevitably cause accidents. Sufficient experience has been gained over the past hundred years of accident investigations by the Factory Department, Managements, Safety Officers, Insurance Companies, and others, to establish beyond a doubt that certain generic groups of parts are accident-producing, irrespective of the particular machine in which they may be incorporated. These groups are given below. Action to safeguard them is preferably taken at the design stage, when the proposed construction of a machine may more easily be amended than later on. It cannot be too strongly emphasized that the proper course is for the machine designer to deal with the guarding requirements except in special cases in which the user makes and inserts his own tools in a standard machine.

THE TWENTY-FIVE GROUPS OF DANGEROUS PARTS OF MACHINERY.* The following groups of parts, or combination of parts, of machinery are intrinsically dangerous, irrespective of the type of machine in which they are fitted:

1. *Revolving Shafts, Spindles, Mandrels and Bars.* (Machine

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* "The Fencing of Dangerous Parts of Machinery," by H. A. Hepburn, B.Sc. (Eng.), A.M.I.Mech.E. (The Institution of Mechanical Engineers, *Proceedings*, 1945, 152.)

shafts, drill spindles, drills, reamers, and chucks, boring-bars, stock bars, vertical traverse shafts on milling machines, etc.)

2. *Inrunning Nips between Pairs of Revolving Parts.* (Gear wheels, friction wheels, calender bowls; mangle rolls; metal manufacturing rolls; rubber washing, breaking and mixing rolls, etc.)

3. *Inrunning Nips of the Belt and Pulley Type.* (Belts and pulleys, plain, flanged or grooved; chain and sprocket gears; conveyor belts and pulleys; metal coiling; cloth batching-up, etc.)

4. *Projections on Revolving Parts.* (Key-heads; set-screws; cotter pins; coupling bolts, etc.)

5. *Revolving Open-arm Pulleys and other Discontinuous Rotating Parts.* (Pulleys; fan blades; spur gear wheels, etc.)

6. *Revolving Beaters, Spiked Cylinders and Drums.* (Scutchers; rag-flock teasers; cotton openers; laundry washers, etc.)

7. *Revolving Mixer Arms in Casings.* (Dough mixers; rubber solution mixers, etc.)

8. *Revolving Worms and Spirals in Casings.* (Meat mincers, rubber extruders; spiral conveyors, etc.)

9. *Revolving High-speed Cages in Casings.* (Hydro-extractors; centrifuges, etc.)

10. *Abrasive Wheels.* (Manufactured wheels; natural sandstones, etc.)

11. *Revolving Cutting Tools.* (Circular saws; milling cutters; circular shears; wood slicers; chaff cutters, etc.)

12. *Reciprocating Tools and Dies.* (Power presses; drop stamps; relief stamping; hydraulic and pneumatic presses; bending presses; hand presses; revolution presses, etc.)

13. *Reciprocating Knives and Saws.* (Guillotines for metal, rubber and paper cutting; trimmers; perforators, etc.)

14. *Platen Motions.* (Letterpress platen printing machines; paper and cardboard cutters; some power presses and similar adaptations.)

15. *Projecting Belt Fasteners and Fast-running Belts.* (Bolt and nut fasteners; wire-pin fasteners, and the like; woodworking machinery belts; centrifuge belts; textile machinery; side belting, etc.)

16. *Nips between Connecting Rods or Links and Rotating Wheels, Cranks or Discs.* (Side motions of certain flat-bed printing machines; jacquard and other automatic looms, etc.)

17. *Pawl and Notched-wheel Devices for Intermittent Feed Motions.* (Planer tool-feed motions; power press dial-feed tables, etc.)

18. *Nips between Reciprocating and Fixed Parts, other than Tools and Dies.* (Metal planer reversing stops; sliding tables and fixtures; cotton-spinning mule carriages and back stops, pillars, etc.; shaping machine tables and fixtures; tool steady guide and steady arm on turret lathe, etc.)

19. *Nips between Revolving Control Handles and Fixed Parts.* (Traverse gear handles of lathes, millers, etc.)

20. *Moving Balance Weights and Dead Weights.* (Hydraulic accumulators; counter-balance weight on large slotting machines, etc.)

21. *Nips between Revolving Wheels or Cylinders and Pans or Tables.* (Sand mixers; edge runners; crushing and incorporating mills; dough brakes; mortar mills; leather-currying machines, etc.)

22. *Cutting Edges of Endless Band Cutting Machines.* (E.g. woodworking, log-cutting, metal- and stone-cutting band saws; cloth-cutting band knives, etc.)

23. *Nips between Gears and Rack Strips.* (Inker roller drives on L.P.P. and lithographic presses; some planing machine drives, etc.)

24. *Revolving Drums and Cylinders—Uncased.* (Rumblers in the foundry; dough mixers; varnish mixers; rag digesters, etc.)

25. *Nips between Fixed and Unidirectional Moving Parts.* (Buckets or hoppers of conveyors against tipping-bars, stops or parts of the framework.)

The guarding of some of the groups can manifestly be dealt with best in the design office, while others, owing to the variations of use or tool design, can only be dealt with by the user, for example group 12.

Principal Methods of Safeguarding. Fixed guards are legally required in preference to other types, but where the nature of the operation carried out renders their use impracticable, other types will require consideration. Although there are numerous kinds of guards, there are only five distinct types, while safety can also be secured by position or by construction.

THE SEVEN METHODS OF SAFEGUARDING. In general, dangerous parts can be made safe by (1) *Construction*, so as to eliminate danger; (2) *Position*, so that they are out of reach; or by the use of (3) Fixed guards; (4) Automatic guards; (5) Interlock guards; (6) Trip guards; (7) Positional safety or Distance guards, or by any combination of these devices or methods. The safety officer and designer should always consult the production management before making a final decision as to the adoption of a particular type of guard, as any suspicion of interference with output will often cause opposition on the factory floor.

1. *Safety by Construction.* The design for a new machine should be examined with the aid of the list of dangerous parts, and modifications should be made to eliminate any such parts by reconstruction or by placing the source of danger in an alternative and safe position if possible, or if not, then a type of guard should be selected with regard to the nature of the machine, purpose and mode of operation.

At this design stage the widest choice of materials can be made for guards and they can be proportioned and fashioned into the design without disturbing the general good appearance.

Examples can be quoted of carefully thought out safety design in the modern precision grinder or milling machine in which motors, belts and pulleys are enclosed in a housing provided with a cast-iron door which can be securely fastened. Gear boxes of capstan and turret lathes are now totally enclosed and cast-iron or other guards are provided for the belt and pulley drives. Flywheels are generally solid or plated to avoid the necessity for discing by the user, but exposed spindles and shafts do not always receive the attention necessary, in view of their danger, excepting those of sensitive drilling machines. These revolving parts can be protected, generally without difficulty, by plain or telescopic sleeves of steel or brass.

All gearing should be completely encased with the guard butting tightly against the machine frame so as to prevent fingers being inserted between the two. Any inspection door or flap should not allow the insertion of fingers into gear nips, and a good arrangement is to provide oiling devices outside the guard.

A common fault in design lies in giving insufficient clearances, such as between control handles and moving tables, or between fixed and moving parts. These traps can easily be rectified in design but only with difficulty in the finished machine.

Care should be taken to shroud automatic trip stops for reversing motions, as on milling machines, because they are a frequent source of "nip" accidents when the machine is in motion, and the developments of hydraulic and pneumatic feeds have accentuated this need. Feed and discharge openings should be such that even if the arm is fully extended inside, fingers cannot reach the dangerous parts, or else the openings should be guarded to prevent access.

Pedals for clutch control should be placed where they cannot inadvertently be actuated by articles falling on them and should preferably be of the safety self-locking type. More attention is required in the placing of control levers and handles in convenient positions so as to prevent fatigue which is conducive to accidents, also such controls should not be too stiff in operation. The finger-light mechanisms of electric, pneumatic or hydraulic devices are far safer than ponderous treadles and levers. The use of different colours for fixed and moving parts, operating handles, etc., lessens the risk of carelessness in operation.

2. *Safety by Position.* The placing of dangerous parts out of reach, as an equivalent to secure fencing, may sound attractive, but in reality the principle is not easy to maintain. It is strongly recommended that for production machinery, guards should be provided for all dangerous parts wherever situated which, if they were within normal reach, would be fenced as a matter of course.

If close fencing, say of gears within the frame of the machine, is impracticable, then some form of guard, interlocked with the starting mechanism, should be fitted so that before the guard can be removed or opened, the machine must be stopped.

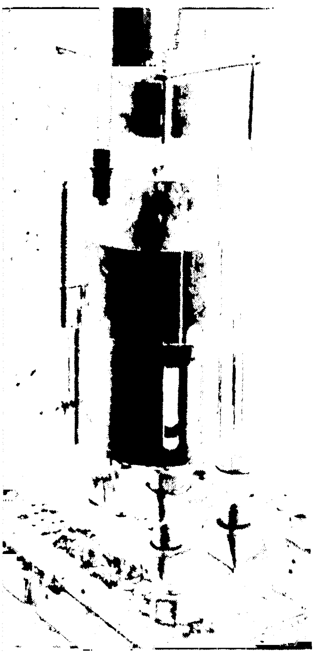

Fig. 23.1. "Reliance" patent guard for sensitive drilling machines (*Alfred Herbert, Ltd.*)

3. *Fixed Guards* should, by their construction and fitting, prevent all access to the dangerous parts, should be of robust construction to withstand rough usage, and wherever possible should form an integral part of and not be easily removable from the machine. Cast iron, sheet steel and expanded metal of small mesh may be found suitable and appropriate, but cast iron should not be used for peripheral guards over abrasive wheels or in any case where it may be subjected to shock. Sheet steel lends itself to fabrication methods and is probably the best and most easily adaptable material, especially for gear guards when an oil bath can be included in the design.

Expanded metal is useful when a clear view of the moving parts is desired, but should be made of small mesh or so fitted that fingers cannot be inserted through the apertures far enough to be trapped.

Examples of appropriate kinds of fixed guards are given in the various safety pamphlets issued by the Factory Department, in Reports of Departmental Committees, etc., so reference will only be made to two modern types.

The guard shown in Fig. 23.1, for the lower portion of the drill spindle, chuck and drill of a sensitive drilling machine, obviates hair entanglement with the revolving parts, a frequent accident where women are employed. It is composed of cylindrical metal portions having sliding contact within themselves, and is provided with a quick-action locking device to hold up the lower portion when setting-up. In operation, the centre slide depresses two light springs which maintain the lower portion in the full guarding position close to the jig or clamp during the entire drilling operation.

Fig. 23.2. Fixed guard for horizontal milling cutter
(*General Electric Co. Ltd.*)

Protection for the cutter of a horizontal milling machine is shown in Fig. 23.2. The dual guard consists of two fixed parts, the upper portion secured to the arbor-supporting arm, the lower, for guarding the under part of the cutter, clamped to the traversing table. The lower portion, forming an enclosure, may consist of a block of wood. Further particulars of guards for drill spindles and milling cutters will be found in the references.

A notable new patented device prevents the opening of a guard, door or other protection for dangerous parts while they are in motion and until they have completely come to rest. Some rolls of machines, for example, are so highly polished that their motion cannot at once be detected; approach to them too soon may result in serious injuries. A sliding bolt engages with a keeper or catch in the guard. When the operating handle is moved to cut out the motor it also starts this bolt withdrawing over a period varying from 4 to 77 seconds according to the time needed for the protected parts to come to rest.

Many accidents occur on *projecting stock-bars* in lathes and cutting-off machines due to the entanglement of hair or of loose clothing. Fencing is best achieved by means of tubular guards but operatives may require a space of about twelve inches or so at the headstock end for the manipulation of the bar and this space should be specially protected to prevent personal contact. A vee-shaped guard under the bar and brought well above it has been successfully adopted for the purpose. Stock-bars should not project beyond the outer end of the guard but should always be cut to the precise length before insertion in the machine and to suit the feed-up mechanism. There is a future for interlocking mechanisms for guarding these stock-bars, the guards being combined with a device to prevent over-long bars being used, and also for feeding-up the stock-bar by pneumatic power.

Where a large opening is required—as in power-press work—for the insertion of an article in the die, it may be possible to adopt the device of an interrupted tunnel or slotted feed opening in the guard which allows passage of the article but not of the operator's hand. Examples of these guards, and others, can be seen at the Industrial Health and Safety Centre, Horseferry Road, London, S.W.1, of the Ministry of Labour and National Service, and are shown in the Power-Press Safety Pamphlet.

4. *The Automatic Guard.* As the name implies, this guard is worked by a moving member of the machine to which it is fitted and is designed to remove the operative away from the point, line or area of work of the dangerous parts before trapping can.occur. It is not suitable on quick-running machines because of the small interval of time available for proper functioning and, notably, because of the effects of high inertia stresses set up in the mechanism during the acceleration periods. Principal examples of use are on heavy and medium power presses.

Friction or slipping devices should not be used for driving automatic guards; positive connection should always be made to a suitable part which moves whenever the machine is set in motion either normally or unexpectedly. Protection is afforded by this guard in the event of a repeat stroke caused, for example, by clutch seizure or other mechanical fault, or due to any other accidental operation of the machine.

5. *The Interlock Guard.* This ensures that the machine cannot be started up until the dangerous parts are fully protected by the guard and that those parts cannot be exposed again until the machine has come to rest. Two forms of interlocking are employed, in the first the moving portion of the guard is connected to a device which prevents the starting-mechanism clutch, fast and loose pulley system, electric motor starter, hydraulic valves, etc., from being manipulated to put the machine in motion until the guard is in the protecting position. This may be termed the *Control-interlock* as distinct from the other type, the *Scotch-interlock,* in which a scotch or some solid piece connected to the guard is interposed between two moving machine parts so as to prevent the starting-up of the machine until the scotch is removed by putting the guard member in the protecting position.

Essential points in the design of an interlock guard are:

A. When the movable part of the guard is displaced from the position of safeguarding, so as to give free access to the dangerous parts, it must be impossible to set the latter in motion, either by accident or intentionally. This must be prevented by interlocks between the guard and the source of motion, to ensure: (*a*) the switching off of the driving motor for unit drive machines, or (*b*) the locking of an essential actuating member of the clutch in the "off" position as near to the clutch members as practicable (in a power press) or (*c*) the interposing of strong stops or chocks between the two moving or closing portions (hydraulic press rams and plates), or (*d*) the locking of the striking gear rod or device of a belt and pulley drive to prevent the belt from returning to the fast pulley, or (*e*) the opening of the exhaust valve of hydraulic or oildraulic presses, or other means to prevent a build-up of pressure behind the ram.

Other devices and methods may be used; for example a mercury contact switch may be incorporated in the moving portion so that when the guard and switch are displaced from the protecting position, the electrical circuit of the motor control is interrupted, thus stopping the motor and applying the brake. Photo-electric and electronic principles offer new and extended scope for protective purposes.

B. Immediately the machine starts the guard should be automatically locked in the closed, or safe, position until the machine has again been brought to rest. This absolutely necessary condition may be achieved in several ways, such as:

(*a*) By interlocking the guard-closing portion with the control mechanism so that the guard cannot be opened until that control has been put in the stopping position and the dangerous parts if rotating have been brought to rest by the load resistance, friction or by means of the specially fitted brake. Practical methods of effecting such an interlock are illustrated in the Laundry and Bakehouse Machinery Safety Pamphlets, the principles being applicable in general to any machine.

(*b*) By interlocking the guard-closing portion with a moving part of the machine, so that the two parts together form a positive lock, independently of the control mechanism, until the dangerous parts have come to rest, when the lock is self-released or opened by hand. The machine starting-up control requires also to be separately interlocked with the guard unless the dangerous parts are prevented by positive means from being set in motion when the guard is open for access.

A typical example, fitted to the power press shown in Fig. 23.3 is that of the "radial slot in disc and pin" type. A disc is carried on the crankshaft and has a radial slot in which can engage a roller carried on the end of a lever connected to the movable portion of the guard. When the machine is at rest, the guard can be opened because the roller can move along the radial slot towards the centre line of the crankshaft. Closure of the guard pulls the roller out of the slot and when the crankshaft revolves, the roller rides on the periphery of the disc which prevents the guard from being opened until the motion ceases and the radial slot is again presented to the roller. Separate interlocking is provided for the clutch actuating control on this power press.

Press guards are now also arranged to work by compressed air through a separate foot pedal, the clutch control mechanism being then actuated to complete "sequential" operation, with improved output. The air closure of the guard eliminates the heavy pressure on the operating pedal which tended to wear the guard mechanism unduly.

6. *The Trip Guard* is particularly valuable for protecting the nips between pairs of revolving parts, or between reciprocating and revolving parts, into which material is fed by hand. The fundamental

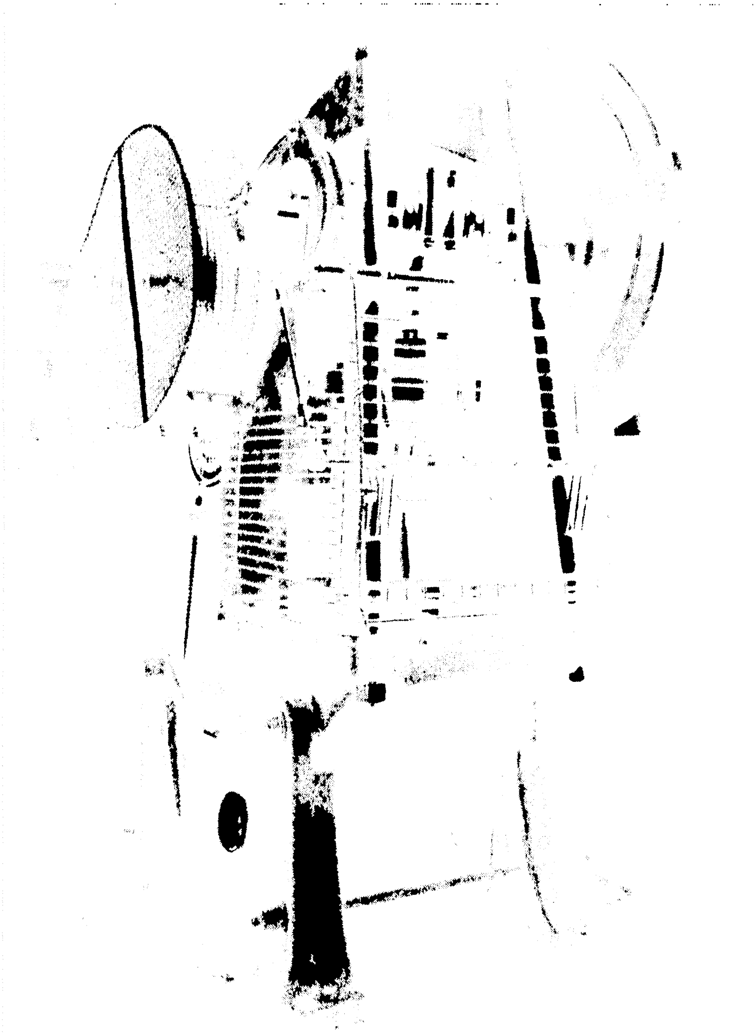

Fig. 23.3. Interlock guard on power press. Note fixed guards for gear wheels and V-belt drive

(*Hordern Mason & Edwards* and *Press Guards Ltd.*)

principle is a combination of a guard and associated tripping mechanism designed to bring the machine to rest, or even to reverse it, before full access to the dangerous parts can be attained.

An efficient guard must work in conjunction with a brake sufficiently powerful to bring the machine quickly to rest. Various forms of this guard exist, the commonest consisting of a hinged plate so arranged as just to allow room for the feeding operation and capable of swinging round the hinge when pressure is exerted upon the plate should danger of a nip be imminent, thereby releasing a spring powerful enough to actuate the stopping mechanism of the machine, so as to bring it to rest and simultaneously to apply a brake. Quick stopping is essential and extreme care in design is required, especially for machines having considerable momental energy such as rubber calenders and mixers, platen printing machines and others, in order not to overstress any of the moving members or framework when the guard is tripped. Bad design has resulted in the stripping of gears or the cracking of side frames; the machine makers should always be consulted to ascertain the minimum period of time in which a machine can safely be stopped. A simple type of trip guard is a rod, wire, or other movable device placed in such a position relatively to the nip of rolls that the operative can stop the machine by clutching the rod, etc., which cuts out the driving motor. Strictly speaking this arrangement is not secure fencing but is useful for supplementing other forms of guards, particularly those of the "Distance" type (see below).

The essence of design for mechanical operation of belt striking gear or clutch disconnection lies in the construction of the actual tripping mechanism which can be made of toggle levers, triggers, or quick-reversing gear. In some arrangements the spring is replaced by mechanical gearing or a screw and nut device for disconnection of the clutch or other drive.

7. *The Positional or Distance Guard* is useful when close-up fencing, by fixed or other guards, is impracticable, but should often be supplemented by a wire or other trip device for quick stopping because access under or over the guard to some machines may be possible in the course of operation.

The usual form is that of a grille or of bars or rails placed at such a height above the floor or standing place, and distance from the trapping line or area, that the arm cannot be extended over the top bar far enough for the fingers to be trapped. Exact location and dimensions are best decided by experiment.

Electronic and photo-electric devices yield promising guards on this principle as they possess the advantage of not interfering with a clear view of, and access to, the operational area. A successful example is found on a self-contained oil-circuit fluid press, separately motorized, on which the feeding spaces at back and front are "guarded" by multiple horizontal light beams. Interruption of any ray stops the ram at any part of the stroke and reverses its motion, a simple operation in this instance, but not so easily applied to heavy machines which may possess considerable momental energy.

Another and most efficient form of this distance principle is that of the "tunnel" guard which is used for preventing access to the nips of feed rollers especially where lattice feeds are employed.

Conveyors of whatever design often involve dangerous nips, for instance those between the belt and end drums in the belt conveyor; these between sprockets and links in the chain system and between plate edges at turns and corners in the flat plate type; apart from those at the actuating gearing. Fixed guards should be provided at all nips.

Non-power-driven Machinery. Inherently dangerous features are found also in these devices: the nips of inrunning gears, as in bench drills; hand cranes, bending machines and others; the blade of a sheet metal cutting guillotine; also nips between rolls of various small machines. The tools of a hand press or of a kick press should be fitted with a suitable guard either of a fixed kind or of the automatic or interlock type (Fig. 23.4).

Portable Electric Tools. Shock and burns with these may be due to lack of proper earthing of their metal frames, or to short circuiting. Low voltage circuit for all portables is strongly recommended;

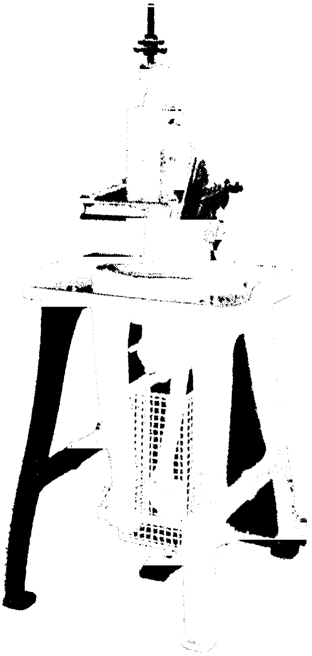

Fig. 23.4. Cage type guard on kick-press

(*Press Guards Ltd.*)

one system is to have a reduction—through a suitable transformer with earthed mid-point—from mains voltage to 100 volts (55 volts to earth) in places where a shock to earth would be serious. Such voltage is recommended in Clause 205 of B.S.I. Code of Practice 321: 1948.

Apparatus designed for this voltage is as light as that for the normal 240 volts and the cable is not much heavier. Maintenance-of the earthing connection is of such great importance as to deserve some special means of control. One recommended system is to have a circulation of current in the earth conductor and the "hold-on" coil of a contactor. Constant attention should be paid to the maintenance of connectors at either end of the feed cable. An isolating switch at the supply end will avert many accidents due to inadvertent switching on of a portable drill while a bit is being changed.

Dust and Fume Control. These risks involve both *danger to health* due to the inhalation or ingestion of, or contact with, the many poisonous, toxic or injurious materials; and *danger from fire and explosion*. There are specific diseases due e.g. to the inhalation of silicon dioxide; to breathing the fine fibres of asbestos; to mercurial, lead and other metallic poisoning, and so on. Fire risk arises not only from organic but also from some metallic dusts such as aluminium and magnesium as well as from the vapours of petrol, benzene, carbon bisulphide and other liquids.

Some substances may be both toxic and inflammable, the gravity of the hazard depending upon the degree of concentration and the size of contaminant particles in the atmosphere.

The first principle for preventing injury to personal health is, if at all possible, to substitute a non-poisonous substance for the dangerous one. If that is not feasible, then other appropriate measures must be adopted. These are (1) *Complete enclosure* of the plant concerned so as to prevent any escape of contaminant into the air of a workroom; (2) *Wet methods* which wash the contaminants away or prevent the dust from becoming airborne; (3) *Removal* of the contaminent by means of exhaust ventilation applied as appropriate to the process; sometimes in addition to enclosure (e.g. in the rumbling of castings). It is highly important that hoods for this purpose should be close enough to ensure an adequate draught, the suction diminishing as the square of the distance from the work. Such devices exhaust, of course, far more air than needed for normal ventilation and may thus affect the latter, especially when heating is in force. But filtering and recirculation are limited by the efficiency of filters, which may pass invisible yet still dangerous dusts, and of course this is out of the question for inherently toxic dusts.

Precautions against explosion of gases and vapours comprise (1) Prevention of formation of an explosive mixture by *dilution* with an excessive quantity of air; (2) *Prohibition* of open lights and flames and of instruments liable to cause a spark; (3) The use of appropriate *flame proof* electrical apparatus; and (4) Proper *earthing* of machines and plant to eliminate static electrical charges.

Some 150 highly explosive dusts are listed by the Factory Department of the Ministry of Labour; these ignite and propagate flame readily and require only a small source of heat for ignition. To produce an explosion in presence of such a source, the dust particle size and the air concentration must in each case be within a certain range. Therefore the necessary precautions will include: (1) the prevention of dust clouds; (2) the exclusion of all likely sources of ignition; and (3) the limiting of the spread and effects of any explosion by the use of suitable explosion reliefs, by sectionalizing of plants, by the use of chokes in conveyors etc.

The dangers from dust by inhalation or explosion depend largely upon the particle size. The risks are greater as the size is reduced; for example, with silica dust, particles of size 5 microns and below are known to be more harmful than larger particles if inhaled. Such small particles are usually invisible in ordinary lighting but it must not be assumed that the atmosphere is therefore harmless. Every effort must be made by all means to suppress dust generated in any dangerous process. The legal obligation under Section 47 of the Factories Act 1937, is to take all practicable measures to prevent the inhalation of any dust or fume or other impurity of such a character as to be likely to be injurious or offensive, or any substantial quantity of dust of any kind (whether poisonous or not).

The range of this subject is extensive; information upon dangerous dusts, gases, vapours and fumes can be obtained fom H.M. Inspectors of Factories who will be able to advise on all necessary precautions.

Radioactive Materials are not likely to concern many readers of this book; but a preliminary survey of the problems they involve may be obtained from the Model Code of Safety Regulations published by the International Labour Office and the draft code issued by the Chief Inspector of Factories (see Bibliography).

Safety Engineering. The rise of this branch of engineering is a feature of the past few years, and fundamental principles are being gradually enunciated to guide those whose function it is to prevent industrial accidents, so far as that can be done by proper design and safeguarding. No objective can surpass that of conserving the individual from the serious consequences of an accident, which are not measurable so much by statistics as by intensely personal experience. The time has arrived when guard design and manufacture must be fully equal to those for the machines upon which they are fitted, otherwise they give but a false security.

The successful adoption of a guard depends greatly upon its reception by the machine operative, so that the co-operation of the production management should always be sought, and their advice considered, before a final choice of type is made, following which, when the guard has been fitted, the machine operator should have the use and arrangement, together with the necessary adjustments, if any, carefully explained to him. Attention to these matters will save much discouragement and wilful misuse of otherwise good guards. There is always the necessity for periodical examination, adjustment and checking-up of all guards to ensure that they are being maintained in efficient working order; this is a job for the safety officer or other trained persons.

Now that the State is responsible, not only for the welfare of the operative, but for his treatment if injured, it is likely that care for industrial safety will become an even clearer obligation of managements. While it is true that a large proportion of accidents are due to human factors, with which we are not here concerned, and others may be caused by factors such as floor obstructions which are organizational rather than mechanical, it is certain that safety engineering must demand increasing attention from engineers and designers.

For Bibliography see end of book.

CHAPTER XXIV

HUMAN RELATIONS IN THE WORKSHOP

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General Considerations. The bulk of this book has been devoted to technological study; to describing the purposes of the various processes through which materials may pass whilst their composition or form is being changed into something required by ultimate consumers. The rapid advancement of knowledge in pure and applied science during the present century has opened up such vast fields of new thought and potential practice that a student may well feel an inclination to devote himself assiduously and even exclusively to the further study of the technological aspects of industry. The apparent advantages to be gained from such a course seem to him so clear and so immediately productive of results.

If such a student be successful, he will achieve happiness in producing a new product, in producing an old product in a new or in a cheaper way, or in finding out new uses for familiar products. He may accomplish these results in a laboratory, at a work-bench, or in a tool-room as an applied scientist. He may make his special contribution, after a prototype has been successfully launched, by steering the product through the period of teething troubles which inevitably arises when prototypes are transferred to the workshop for bulk production. In either case he will tend to concentrate his interest on ideas and on things. Therein lies a danger, not merely affecting the student himself, but also that very technological efficiency which he desires so earnestly to pursue.

Industry involves something more than ideas and things. It involves people. Good material, good plant and equipment, competent research, good technology, and good organization of the workshop will all fail in their primary purpose of producing goods for consumers unless an equal amount of thought and care are taken in dealing with the human beings who are responsible for carrying out the whole of the duties involved in an industrial undertaking. The danger to the student arises in that he may develop his technological specialization to such a degree that it absorbs him to the exclusion of everything else. He becomes an excellent fellow in the world of ideas and things, but hopelessly inefficient in dealing with people. He is not fitted to be put into a position of authority where he can demand action of others; he tends to live more and more to himself; lamenting that human beings are not so tractable as things, becoming more dictatorial in outlook and manner, and thus failing to inspire his colleagues and subordinates with his own devotion to their joint purposes. He does not obtain that co-operation from others which is so essential to the well-being of a common enterprise.

Industry as a System of Human Co-operation. Industry to-day is a very important form of co-operative activity. Its aim is service to the community, primarily in the production of goods, but in pursuing its primary aim it must not lose sight of the fact that it takes up a large portion of the lives of those engaged in it. Since industry is not the only form of group activity—politics, education, and religion are examples of other forms—it would seem reasonable to expect that industry should supplement those other forms by enabling individuals, through co-operation with others, to lead a full life and to make their contributions to citizenship in its widest sense. Industry conditions, and is itself conditioned by, the other aspects of life which lie outside it. Industry cannot expect individuals to be one thing in their general lives and something else immediately they have entered the gates of a works. They bring their sense of perspective, their emotions, hopes, and fears with them. Above all they want to feel that they belong to the undertaking, that that undertaking and their places in it have the respect of other men, and that their own contribution is going to be effective.

So many important issues arise from these conceptions that a chapter such as this can do little more than chart the field of study of human relations with particular regard to their importance in the workshop, and to offer a selected reading list to which further reference should be made. In offering what follows in the present instance, the writer has been very conscious of the difficulties of selecting for special emphasis those things which might provide a minimum foundation upon which to build a structure of relationships. It must also be remembered that circumstances, people, and past history—all relevant factors—vary from undertaking to undertaking, and therefore principles rather than mechanisms must be outlined.

It is of first importance that there should be in existence, exhibited in appropriate parts of the premises, diagrams or charts showing the relationship of workers to their supervisors and of the members of the supervisory force to each other. The chain of authority should be clearly indicated and the special authority of experts not in direct line of authority—such as time-study men, personnel officers, and inspectors—should be clearly explained to all concerned. Failure to do this results in disorder, bad feeling, slowness in action, and general ineffectiveness all round. Some may argue that clearly defined duties result in inflexibility, or in a lack of freedom to act as occasion warrants. The answer is that in normal working, flexibility is a desirable aim, but not in this particular aspect of organization. Experience has amply shown that no one should give orders except to his immediate subordinates, save in case of emergency.

Personnel Policy and Personnel Management. If managers and managed are to work together as a team, it is reasonable to suggest that this feature will be at its best if it results from a deliberate policy rather than from the caprice of chance. That aspect or function of management which concerns itself with people and their relationships one to another in a business is called "personnel management", which must start with a "personnel policy" decided by the directors. Both personnel policy and personnel management are integral parts of any undertaking whether the implementation of the policy is or is not made the responsibility of a Personnel Department. Personnel policy will have something to say on the questions of engagement, selection, promotion, discharge, wages and conditions, relations with organized labour (trade unions), joint consultation, health and safety, employees' services, and education and training. Merely to look at this list should be enough to convince us that the field it covers is both wide and complex, and that a line official, responsible for all the technical aspects of production, should be most grateful to a Directorate which considers that he should not be burdened with policy-making or the carrying of ultimate responsibility in personnel matters. Unfortunately, many concerns are of small size, and therefore cannot provide full-time employment for a Specialist Personnel Manager. In such cases the Technical Manager has necessarily to undertake this work but, even where a Personnel Manager is employed, his status will only be advisory. No matter how good the Personnel Manager may be, and no matter how excellent the personnel policy he advocates, results will not be forthcoming unless the policy is consistently implemented, hour by hour, by the line executives and supervisors, in their dealings with operatives on the floor of the shop.

Personnel policy might well have as its background the idea that the work should be considered by all concerned as worth doing; that the available technique should be adequate for the work; that management should be efficient; and that the mental and physical environment for those employed should be the best which can be devised. Given these conditions, it might well be hoped that employment at such a concern would be a source of legitimate pride to all grades of workers, and that a conditioned climate of employment would have been provided in which participants could enjoy full and satisfactory industrial life. There would also be a basic understanding that all possible steps would be taken to ensure continuity of employment for satisfactory workers.

Policy itself would insist on adequate care being taken in the engagement of personnel, in the avoidance of the placing of "square pegs in round holes", in introducing beginners to foremen, in systematic follow-up of newcomers until they have been absorbed, in the keeping of adequate records and statistics concerning each person employed so that promotions may be decided upon with adequate data, and not haphazardly or as a result of nepotism or favouritism. All this is involved in the employment function of personnel management.

With regard to wages and hours, the personnel policy would decide on such matters as the methods of wage payment, the inauguration of bonus schemes, methods of time-keeping and hours of work. More fundamentally still, it might determine that the net earnings of the concern would be distributed amongst the shareholders, the employees, the customers and the concern itself, having regard to its future stability and development, in a manner which would be considered reasonable and fair, and giving interest and incentives to all.

It is practically certain that in the engineering industry many, but not necessarily all, employees will be members of organized trade unions. The concern itself might or might not be affiliated to one or more employers' associations. National agreements entered into by the industry as a whole would therefore have to be implemented within the concern and arrangements made for negotiating with trade unions by the methods of conciliation and/or arbitration should the occasion arise. It should be noted that national agreements usually lay down wages and conditions which are to be regarded as minima, and the provisions of these agreements, including procedures to be adopted in case of any disputes, are matters in which the concern must act in conjunction with other concerns and the trade unions. It is not possible for the concern to act on its own.

Joint Consultation. There are certain aspects of employer-employee relationships, however, in which a concern may act independently and about which it can frame its own policy. These bring us to the question of Joint Consultation. Any organized society has a framework of rules for the orderly conduct of its affairs, and an industrial works should be no exception. In ordinary life, our rules are the laws of the country, and in a democracy the rules or laws are made by the elected representatives of the people themselves Modern views in industry also hold that works rules, the violation of which might incur penalties, should be framed by the management after full consultation and agreement with the managed. This is the initial step in policy-making which enables employees actively to participate in management. The initiative obviously rests with the management, and the first requirement is a scheme whereby employees of all grades can choose their representatives. Modern experience has shown that danger lies in elected representatives getting out of touch with their electorates, and wise representatives take care to ensure an adequate system of reporting back to their constituents. In an intimate society like an industrial works, it is becoming accepted as proved by experience that one person cannot adequately report back and note the detailed reactions of more than twenty to twenty-five people. Hence twenty-five people is ideally the maximum "constituency" and would be entitled to one representative. Thirty such representatives could form the Works Council and represent 750 employees. In larger concerns a secondary layer of Departmental Councils would be required and these could deal directly with departmental matters, leaving only major issues to go to the Works Council. Here is a case where only the outline of a pattern can be drawn and general principles stated, leaving actual mechanisms to be decided upon in the light of particular circumstances.

But the framing of Works Rules is only one task for Joint Consultation. It can also address itself to the problems arising from grievances and complaints concerning bad local working conditions. By a series of sub-committees it can advise the management and co-operate with it in solving current problems of production, safety, and absenteeism. Its committees can also advise on Canteens, Sick Clubs, Recreational and Social Schemes, Suggestion Schemes, and on problems connected with Education and Training. Such an all-embracing scheme of Joint Consultation can enable employees to make a maximum contribution to management policy, and give the requisite conditions whereby an externally imposed discipline is changed into a more efficacious self-imposed discipline. Joint Consultation can reduce the tempo at which disputes arise and grow; it can provide the opportunity for educating workers in managerial problems and in the techniques of overcoming them. It engenders a sense of responsibility in the workers. It ensures that management keenly scrutinizes proposals before propounding them so as to make certain that they are necessary and reasonable. It helps managers and managed to know each other better—an essential condition of their living in harmony together—and it gives rise to hopes that after working together harmoniously on smaller things, the two partners will be more ready to integrate their interests with that of the whole community in the greater things.

Personnel policy, as regards health and safety, will presumably start with the observance of the Factories Acts—both in the spirit and in the letter of the law—as the minimum requirements for the concern. It will address itself to the problem of the provision of an adequate works' medical service, the establishment of physical standards necessary for different jobs, the close supervision of jobs dangerous to health, and the encouragement of enthusiastic support of accident prevention and all its implications on the parts of all concerned.

Employee services might include the provision of a canteen, personal services such as dentistry, chiropody, hairdressing, and the provision of a person experienced in social work to act as counsellor and adviser to employees in difficulties of any kind. A good personnel policy will recognize the fact that what happens to an employee outside the shop has often a great bearing on his or her conduct and efficiency whilst in the shop, and will take a positive line on the matter without attempting in any way to interfere with the lives of employees outside the works.

Education and Training. Finally, personnel policy must deal with education and training, deciding what training shall be undertaken within the works and what training shall be left to the Local Education Authority and other outside provision. A valuable distinction may be drawn between "education" and "training" in so far as the first denotes knowing "why", whilst the second is concerned with knowing "how". Alternatively, it is suggested that education has for its aim the acquisition of knowledge and understanding, whilst training aims at the acquisition of skills. Viewed in this way, it is clear that education and training are complementary to each other, but whereas education can be provided anywhere, at least those sections of training which are inherently concerned with particular industrial situations must be undertaken on the actual site or in that particular environment.

It would thus appear that the training of apprentices and new workers as well as the training of unskilled workers in readiness to take over semi-skilled jobs, and the retraining of workers on changing jobs, might all be undertaken within the concern itself. Many of the medium-size and most of the larger concerns now support regularly established training programmes under the direct supervision of an Education and Training Officer, who is a member of its own staff. His duties might also include the provision of suitable courses in Safety and Accident Prevention and in Chairmanship and Committee Procedure for all those elected on to Joint Consultation Committees.

In the smaller concerns, where the employment of a full-time Education and Training Officer is not an economic proposition, the education and training function should be clearly assigned to a senior line executive. He will, in turn, be assisted by Departmental Heads and Foremen, and more recourse to facilities provided by the general educational system will be necessary than is the case with the larger concerns.

Whether the undertaking be large or small, the results of training are likely to be higher if the trainers have themselves been trained for the job they are doing. Skill at imparting what one knows to others is not inborn in everybody. It is an art with its own "know-how", and though a knowledge of the art will not make everyone good practitioners, time spent on the rudiments and methodology will help all to become better teachers.

The Training Within Industry (T.W.I.) programme, now supplied as a free service to employers by the Ministry of Labour and National Service, with its three courses in Job Instruction, Job Relations, and Job Methods—addresses itself precisely to solving problems associated with the training of trainers. Short intensive courses are arranged wherein supervisors are trained, firstly to improve their skill in instructing others; secondly, to improve their skill in handling other people; and thirdly, to show them how best to attempt the task of improving the methods by which jobs under their supervision are done. It is essential for the success of this scheme that it has the enthusiastic backing of those in higher authority at the undertaking. The Job Relations programme is of immediate and direct interest to the subject-matter of this chapter, but the other two programmes are integral parts of a complete whole which, if intelligently applied, will, in the present writer's view, affect human relationships in industry for the better. Those with industrial experience will probably agree that poor training lies at the root of many minor difficulties found in a workshop. The aggregation of such difficulties and the accompanying sense of frustration or inefficiency are potent factors in the breakdown of good human relations.

Generally speaking, the technological, technical, and general education required by candidates who desire promotion to higher grades is provided outside industrial concerns at Universities, Colleges of Advanced Technology, Technical and Commercial Colleges, or at meetings, conferences and courses provided by professional and kindred bodies such as the British Institute of Management, the Industrial Welfare Society, the Institute of Personnel Management, the British Association for Commercial and Industrial Education and similar institutions. Many undertakings encourage their employees to attend such courses by granting time off by part-time day release from the works and by the payment or part payment of fees.

The British Productivity Council and its branches throughout the country offer conferences and meetings to managers and operatives alike in an attempt to increase industrial productivity as a whole in the national interest. One of its main activities has been and is still concerned with Work Study, whose introduction and implementation may cause much friction at shop-floor level. Given goodwill at the beginning, the chief cause of such friction is misunderstanding, and many Technical Colleges have undertaken the task of clearing away suspicion and ignorance by providing Appreciation Courses and Practitioners' Courses in this field.

The use of outside resources by industry in the field of education and training is usually found where, for any reason, the service cannot be provided by industry itself, or where there are positive advantages to be gained by allowing the participants to be taught in a "disinterested" manner in an environment which allows outlooks to be broadened by contact and discussion with other students from other concerns and other industries. Good human relationships in industry rest on a good personnel policy continuously implemented throughout an undertaking, and in the last analysis it is not the mechanisms but the attitude of mind upon which success depends.

Works Discipline and Industrial Justice. Under the heading of Joint Consultation it was noted that good human relations in a workshop would be more likely to exist if managers and managed could agree on a set of Works Rules to govern the conduct of all concerned in the undertaking. No community is perfect, and occasions inevitably arise when the Works Rules—the Code of Common Conduct—are broken. When this happens outside the works in ordinary life, the utmost care is taken to ensure that the alleged malefactor is given a fair trial. Our British judicial system is one of which we can be justly proud, and is the admiration of the civilized world. The mechanism of the Courts is sufficiently well known to all to require no great elaboration here, but note can be made that justice is not in the hands of Parliament which makes the laws; there is an independent judge, the right of trial by jury, and the right of appeal.

It is very rare indeed that an industrial works makes provision for a similar system for the dispensing of justice. More often than not justice is meted out summarily and even arbitrarily with managements acting as law-makers, prosecutors, and judges. The only right of appeal a worker has is that of asking his trade union to interest itself in his case, make representations to the employer, and if satisfaction is not forthcoming to threaten, and, if necessary, take strike action. Hence bargaining strength rather than absolute justice might be the arbiter in such a dispute.

During the second world war the Essential Works Order provided that an employer could not discharge a worker, nor could a worker leave his employment, without permission from a government official known as the National Service Officer. Even his decisions could be made the subject of an appeal by either party to a Local Appeals Tribunal. This was the first occasion in British industrial history when justice, in connection with happenings in a works, was by law of the land referred to a person or body of persons outside the works. With the repeal of the Essential Works Order at the close of the war, this system was discontinued, but its existence had made more people than ever aware of the unsatisfactory nature of the old system, and many minds are now exercised in devising improvements for the future.

Notice might be taken, however, of the undoubted fact that industry could incorporate into its schemes a far better plan for ensuring justice to employees than has obtained in time past with inestimable benefit to human relations in its factories and workshops.

It is not the intention to leave the reader under any impression that British industry is reeking with innumerable cases of gross injustices, for trades unionism is organized sufficiently strongly not to allow that to be the case, even if all managements were bad—which they are not. Nevertheless, we have seen that bargaining strength is not likely to ensure justice to employers or to workers, and the establishment of judicial mechanism in industry more in keeping with practice outside industry would be of the utmost value.

Before leaving this topic, there remains one highly significant point to consider. Legal action, even in ordinary life, though essential for the well-being of the community, usually leaves somebody dissatisfied. In all cases involving civil law—and we are not discussing crimes in this connection—it is best only to go to law in the last resort. The process of mediation is much more likely to lead to an amicable settlement of differences. Similarly in industry, it would be good to have a formally agreed scheme of tribunals for administering justice in accordance with the Works Rules, but it would be better for each undertaking to appoint a person as mediator (probably the Personnel Manager) who would act in all cases of breaches of Works Rules. The formal processes of hearing and pronouncing judgment would not be resorted to until all efforts of the mediator had failed.

The Giving of Orders. Both efficiency and good personnel relations between supervisors and workers are conditioned by the way in which orders are given and received. Somebody has to initiate action for something to be done. The person requiring action from others in pursuit of the common purpose is not giving vent to his own whims and fancies; he is implementing policy, which has been explained to him by his superior, after having taken into account all the relevant known facts of the situation in which action has to take place. Giving orders to others is an art, and various writers—but particularly Mr. F. J. Burns Morton in the issue of the *British Management Review* quoted in the Bibliography at the end of this book—have tried to develop the technique.

Mr. Burns Morton points out that executives are often at fault in giving orders by failing to take all the facts into account, omitting to consult or to advise all the people concerned, issuing them to people inadequately trained to receive them or with insufficient explanation, issuing them verbally when their importance deserves writing, issuing too many orders at once, and issuing them without paying sufficient attention to the intelligence of those who receive them. In none of these cases is the executive likely to obtain the keen co-operation of those to whom instructions have been given. Executives also err in failing to follow up orders after they have been issued.

It is becoming increasingly recognized that orders issued to "hands" working *for* you are not as successful as orders issued to "people" working *with* you, and backed up by any necessary explanations as to why the instructions have been issued in precisely that particular way.

As Mr. Burns Morton suggests, orders correctly given should get results, properly direct those from whom action is required, minimize the supervision needed, ensure prompt execution, induce a favourable response, and advance industrial relationships by building up sound team-work. Executives will therefore take care to avoid giving those receiving the orders the idea that they are being bossed, that discipline is too inflexible and does not change in the light of circumstances, that those at the receiving end of the orders are consistently ignored and given to understand that "theirs is not to reason why", and that there is no need to consult them when major changes are taking place. A good executive will also not be indifferent to or deal negligently with genuine complaints and grievances. Genuine friendliness without familiarity, the giving of encouragement when it is due, and identifying himself with his subordinates, are all matters to which a supervisor will pay attention, as well as taking pains to see that all orders issued by him are reasonable.

Leadership and Morale. Morale means "moral condition—especially as regards discipline and confidence", and the state of morale amongst people in a workshop or any other enterprise depends largely on the way those people are led. Morale is a most desirable thing in any system of human co-operation, and indeed is one index of success achieved. It has been argued that doubling the state of morale is equivalent to doubling the number of people engaged in an undertaking. Industrialists have recently been giving much thought to improving our standards of leadership and industrial morale.

Good morale is engendered by good objectives and good purposes. They must be understood by those participating in the activity and must commend themselves to those concerned, who will respond the more readily if they are given an opportunity of making their contributions to policy-making and to methods whereby the objectives can be successfully reached. Enthusiastic interest will develop a willingness to play for the team and loyalty which otherwise would not exist. Given good objectives and good leadership, there are many industrial instances which show that work need not be done under the best possible conditions, or even with the highest rates of pay, to get a magnificent team spirit. All of us wish to feel we "belong" to any group whose activities we join. We like to be proud of being members of that group, we want social approval and sympathy with the objectives of our enterprise, and within the group's activities we wish to preserve our self-respect and our freedom of thought.

The responsibility for building up morale rests on all those who supervise others. Our immediate superior tends to represent in our minds the institution to which we belong. Therefore the quality of leadership must be all that could be desired. Leadership does not mean domination, and good leaders encourage constructive criticism and discussion. They encourage their subordinates to tell the truth and not to develop into "yes-men". Good leadership will tend to develop initiative on the part of those being led, but domination would discourage such initiative and even suppress it.

"All power corrupts", in the words of Lord Acton's celebrated dictum; but the good leader will be on guard against that tendency. He will always be trying to make the enterprise more attractive, and to make his subordinates realize their personal significance in the success of the enterprise. He will ensure that facilities are offered to everybody to improve their knowledge and to do things more perfectly, for doing a job well develops mental interest which gradually spreads to other things. In this way the leader induces those working with him to discipline themselves—the best form of discipline—rather than rely on enforcing discipline from above. Many industrialists have been wise in trying to emulate the methods of Viscount Montgomery with his armies during the last war.

The National Institute of Industrial Psychology has pioneered the idea of holding "Attitude Surveys" in industry. Confidential interviews are held with workers and junior management to find out their reactions to things which happen in the general running of an undertaking. No specific questions are asked, and interviewers wait to see what subjects people bring up spontaneously for discussion. It has been found that tremendous interest is taken in the Higher Management, who influence profoundly those in lower grades by selecting the right people for promotion to executive grades, by efficient organization, and by making wise judgments on matters of policy and practice. Leaders must be reasonably accessible and not remote or too busy to be seen. People expect their leaders to have a sense of justice and fair play, to be reliable, sincere, imaginative but not too far in advance of themselves, capable of receiving suggestions for incorporation into their plans, and—but by no means least in importance—they expect their leaders to be effective speakers.

Conclusion. This brief survey of some of the more important factors which tend to maintain good human relationships in the workshops will have failed in its purpose if it has not convinced the reader of the necessity to dig deeper into the whole subject. A student who has succeeded in satisfying his examiners as to his technical competence will no doubt be well aware, especially if he has industrial experience, of the fact that successful workshop practice depends on things other than technology. Comprehensive courses leading to a Diploma in Management Studies are now available at Technical and Commercial Colleges in the larger towns of the United Kingdom. They are intended for students who have completed their technological and commercial education, and cover a wide range of management subjects. Human relations in industry get the special emphasis they warrant at Final level. These courses are designed for those aspiring to Higher Management, but separate courses also exist for those who have just entered or wish to enter the supervisory grades in industry. In both these types of course the aim is education rather than training, and the development of managerial skills still remains a problem for solution at individual concerns. The present writer can only commend these facilities to students for their earnest consideration.

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SOME METRIC AND OTHER CONVERSION FACTORS

LENGTH

1 in. = 25·4 mm
1 ft = 30·48 cm
1 yd = 0·9144 m
1 cm = 0·3937 in.
1 m = 3·2808 ft
= 1·0936 yd

AREA

1 in^2 = 6·4516 cm^2
1 ft^2 = 929·03 cm^2
1 yd^2 = 0·836 m^2
1 cm^2 = 0·155 in^2.
1 m^2 = 10·76 ft^2
= 1·196 yd^2

VOLUME

1 in^3. = 16·3870 cm^3
1 ft^3 = 0·0283 m^3
1 yd^3 = 0·766 m^3
1 cm^3 = 0·061 in^3.
1 m^3 = 35·315 ft^3
= 1·308 yd^3
1 gallon (Imp) = 1·2 gal (U.S.)
1 litre = 0·22 gal (Imp)
= 0·2642 gal (U.S.)

WEIGHT, MASS

1 oz = 28·35 g
1 lb = 0·4536 kg
1 kg = 2·2046 lb
1 slug = 14·59 kg
= 32·174 lb
1 kg/cm^2 = 14·22 lb/in^2.
1 lb/in^3. = 0·0703 kg/cm^3
1 lb/ft^3 = 16·018 kg/m^3
1 cwt = 112 lb
(hundredweight) = 50·8 kg
1 ton = 2,240 lb
= 1,016 kg

FORCE, WORK, POWER, HEAT

1 poundal = 1 lb/ft/sec^2 = 0·138 newton
1 pound force = 1 lb f = 4·448 newton
1 lb f/in^2. = 0·07 kg fcm/^{2}
1 lb f/ft^2 = 4·882 kg f/m^2
1 ft lb f = 0·1383 m kg f
1 B.t.u. = 778·26 ft lb
= 0·2931 W
= 0·252 k cal
1 C.H.U. = 1·8 B.t.u.
= 0·4538 k cal
= 1,400·88 ft lb
1 h.p. = 33,000 ft lb/min
= 1·014 C.H. or P.S.
= 746 W
1 CH (metric horsepower) = 735·5 W
= 0·9863 h.p.
1 Watt-hour (Wh) = 2,655·4 ft lb
= 3·412 B.t.u.
= 1·896 C.H.U.

INDEX

Abrasive slurry, in ultrasonic machinery, 218–19
Abrasives—
  for grinding-wheels, 187
  for ultrasonic machinery, 223–4
  use of in lapping gears, 287
Absolute dynamic viscosity, 551
Absolute kinematic viscosity, 551
Acceptance test of machine tools, 45, 46–50
Accuracy—
  in spark machining, 300–1
  in ultrasonic machining, 226–7
  performance of, 44
Acid, stearic, 520
Acid refining, 522, 523
Acidity, 552
Acids, fatty, 520, 523
Acme threads, 406
Addendum, 253 *ff.*
  of gears, 247, 249
Addendum modification, 255
  calculation of, 256–7
Additive oils, 524
Adhesion, 77
Adhesion forces, 62
Adjustable gauges, 392
Administration, factory, 575
Aero-engine cylinders, surface texture of, 472–3
Air gauges, 376–7
Airy points, 365
Alignment—
  of grinding machines, 214–15
  of machine tools, 42 *ff.*
Alignment tests, specification of, 45
Allowances, 378–83
  defined, 380
Alloy, copper, as tool material, 300
Aluminium, as tool material, 300
  broaching, 167
  coolants for, 167
Aluminium oxide, 187
  in abrasives, 187
Aluminium-base greases, 525
Amplitude of vibration, 72, 73
Anderometer, 463
Angle—
  clearance, 83
    effect of on tool wear, 88–9
  commercial standards of, 367
  gear pressure, 246, 247
  helix, of gears, 249
  hook, 165
  normal pressure, of gears, 250
  pitch, of gears, 250
  transverse pressure, 251
Angle of rotation of cutter, 116, 118
Anode, 292, 293, 315
Anodic machinery, 313–15
Anodic saw, 314
Anodic tool-grinder, 314–15
Anti-foam additives, 524, 527
Anti-friction bearings, 529
Anti-oxidant additives, 524
Anti-rust additives, 524
Anti-wear additives, 524
Anvil, gauge, 392–3, 396
Aperture, numerical, 419
Apprentices, training, 619
Aqueous cutting fluids, 538–41
Arbors, milling, 123–8
Arc disintegrators, 290–1
Arc machinery, 290–1
Arc of contact, in grinding, 192, 193–4
Arc welding, 290
Arcing indicators, 296
Artificial abrasives, 187
Asbestos fibre, dangers to health, 610
Assembly, selective, 384–5
Assembly processing, 585
  multiple-spindle drilling, 155
Attachments—
  drilling machine, special, 160–2
Attitude surveys, 624
Automatic drilling machines, 156–60
Automatic guards, 600, 604–5
Automatic internal grinding machines, 205–6
Automatic lathe, 108–15
  tool life on, 94
Automatic systems of lubrication, 536–7
Automobile stampings, 343, 344
Automotive gearbox gears, 281–2, 284, 288
Axial float of lead screw, 48
Axial float of spindle, test of, 47
Axial pitch, definition, 249

Back cone, 249
Backlash, gear, 249, 258
Balancing of grinding wheels, 188–9
Bar, sine, 371
Bar gauges, 389, 394
Bar stock, ground, 210
Bars—
  danger from revolving, 598
Bars length, 364–5
Base circle, of gears, 249
Base helix, of gears, 249
Base pitch, transverse, 251
Basic rack, of gears, 249
Basic standardization, 592–3
Batch type furnaces, 564–6

Bath, electrolytic, 315
Bath oiling systems, 547
Bauxite, 187
Bearings—
  full-film lubrication of journal, 517
  grinding machine spindle, 215–16
  lubrication of, 529–33
  machine tool, 36–7
  surface texture and, 473
Bell-type furnace, 565–6
Bench micrometer, 371–2, 400, 401
Bending press, 349, 351
Bending, 342
Bevel gears, 249 *ff.*, 264–5, 270–1
Bibliography, 627 *ff.*
Bielby layer, 419
Bielby's theory, 419, 421
Bilateral tolerancing, 380
Bitumen, 523
Blank, drawing from a flat, 321–6
Blank and draw tool, combined, 356
Blank and pierce tool, combined, 353
Blank-holders, 321, 353
  double-action press, 348
Blank-holding pressure, 333, 345
Blank-holding requirements for re-drawing, 326
Blanking, 342, 347
  load in, 337–9
  ultrasonce, 218, 228
Blanking pressure, 344
Blanking tool, 353
Blanks—
  cutting, 272
  hobbing, 277 *ff.*
Blasting, shot, 482
Block, universal measuring, 405
Bluntness, tool, 83
  effect on built-up edge, 60
Body, design of machine tool, 22–8
Bolts—
  thread errors of, 408
  tolerance of, 406
Bonds for grinding wheels, 188
Boring, 476–8
  cutting fluids for, 545
Boring machines—
  design, 24, 26
  fixtures for, 507–9, 509–10
  vertical, 107–8
Bores—
  grinding, 211–12
  splined, 511–12
Boron carbide, 223
Boundary lubrication, 519–20
Bourdon pressure gauge, 377
Box, drawing a rectangular, 333–4
Box furnace, 564
Brake press, 349, 351
Brass—
  as tool material, 300
  broaching, 167
  coolants for broaching, 167
Break down, lubricant, 520
Breakages, drill, 502
British Association screw threads, 405–6
British Management Review, 622
British Productivity Council, 620
British Standard Fine thread, 406
British Standard Whitworth thread, 406
British standards, 594, 595, 596
British Standards Institution, 392
Broaches—
  design of, 164–6
  internal, 164
  manufacture of, 168
Broaching, 163–72
  advantages and limitations of, 168–9
  cutting oils for, 544
  equipment for spark erosion, 295 *ff.*
  history of, 163–4
  keyway and spline, 510–12
  spark erosion tools for, 301, 303
Broaching fixtures, 510–12
Broaching machines, 169–72
  hydraulically-operated, 167
Buckling, 320
Budgeting, production engineering, 584
Built-up edge, 55, 57–60, 75
Bulging, drawing process, 336
Bushes, drill, 501
Buttress threads, 406

C-TYPE press frame, 346
Calcium soaps, 525
"Caliblock", 442
Calibration of surface texture measuring instruments, 441–3
Calliper gauges, 396, 409, 411
  vernier, 369–70
Cam-action clamp, 492
Camera, electron diffraction, 421
Canteens, 618
Capric acid, 523
Capstan lathe, 108–15
  tool life on, 94
Car bottom furnace, 564–5
Carbide, boron, 223
Carbo-nitriding, 556
Carbohydrates, 523
Carbon residue of oils, 553
Carborundum, 187, 224
Carelessness, safeguards against, 598
Case-hardened bevel gears, 283
Cast iron—
  as tool material, 300
  broaching, 167–8
  straight edges, 369
Cast link, chain and slat belt conveyors, 567–8
Cast replicas, of surface textures, 468–9
Cathode, 293, 315
Cathode-ray oscilloscopes, 296
Cavitation, 222
Cellulose acetate sheet for cast replicas, 468
Cemented carbide grinding wheels, 188
Centre-line-average, 450
Centreless grinding, 195, 209–12
Centrifuges, oil, 547
Ceramics, ultrasonic cutting speeds in, 225
Chalk, 527
  as lubricant, 521
Characteristics of sheet-metal drawing, 316–17
Chasers, screw-cutting, 229–30
Chatter, 71, 72, 73
Chatter marks, 416, 427, 464
Check gauges, 405
  plug, 404

Checking grinding machines, 215
Chip formation, 53–60
  in broaching, 166
Chip thickness, 116, 118, 128–9
  undeformed, 88, 90
Chip-breaker grooves, 167
Chips—
  continuous, 75
  discontinuous, 75
  forces acting on, 65 *ff.*
  types of, 53–60
Chlorinated cutting oils, 543
Chlorinated waxes, 521
Chucks—
  for grinding, 186
  revolving, for horizontal drilling, 160
Cincinnati "Filmatic" bearing, 37
Circle—
  base, of gears, 249
  pitch, 250
  radius of rolling, 456
  reference, of gears, 250
  root, of gears, 251
  tip, of gears, 251
Circuit—
  discharge, in spark machinery, 311
  spark machinery electrical, 294–5
Clamped drawing, 317
Clamping load, 492
Clamping pressure, 320–1
Clamps, milling fixture, 491–7
Clapper box, 179–80
Clay. W. E. R., 418
Clearance, bottom, of gears, 249
Clearance, side, spark machinery, 298–9
Clearance angle, 83
Clearance fit, 380
Cleveland apparatus, 550
Climb milling, 192
"Climbing", 130
Closed flash point, 550
Clutch cover, by forming, 335-6
Clutch drive, 8, 11
Coefficient of friction, 513, 530
Coefficient of hydrodynamic friction, 517
Coefficient of viscosity, 516
Coining, 342
Cold pressing, 351–7
  lubricants for, 358–9
Collet, of grinding machine, 186, 188, 189
Colloidal suspension, 526
Comma, 116
Commercial standards of angle, 367
Comparators, 373–4, 377, 401
  high-magnification dial, 400
  horizontal, 401
Component cutting forces, 79–82
Components, interchangeable, 378, 385
Compound dividing, 140
Compounded oils, 523–4
Compounded cutting oils, 538, 541
Compounds, lubricating, 358–9
Concentric grinding, 211
Cone, back, of gears, 249
Cone distance, gears, 249
Cone pulley drive, 8
Consistency of grease, 525
Construction of safeguards, 600, 601–2
Consultation, joint, 617–18
Contact—
  arc of, 193–4
  gear, 267–8
  line of, gears, 250
Contact zone, gear lapping, 288
Continuous chip, 55, 57
Continuous indexing table-type drilling machine, 157–8
Continuous-type furnaces, 567–71
Control—
  by gauging, 389 *ff.*
Control, dust and fumes, 610–11
  of size by measurement, 385
  quality, 378, 385–405
Control limits, 386, 387, 388
Control wheel, grinding machine, 210
Conveyors—
  cast link, chain and slat belt, 567–8
  safeguarding, 609
Coolants, 537 *ff.*
  for broaching, 167–8
  in ultrasonic machining, 226
Cooling bearings, 529
Copper as tool material, 300
Copper graphite as tool material, 300
Copper stearate, 520
Conradson test, 553
Corner radius, in drawing, 333, 334
Corrective ironing, 317
Corrosion—
  protecting machines part from, 529
  risk of with cutting fluids, 537, 539 *ff.*
Corrtherm element, 556
Corundum, 187
Cost, standardization and, 591
Crank press, 343, 344–5
Crank shaper, fixed head, 174–6
Crankshafts, grinding, 201–2
Crater—
  in tool wear, 85
  spark-erosion, 293
Crest, screw threads, 408
Crest line measures, 450, 452
Cresylic acids, 523
Cross-slide, tests for, 49
Crossed helical gears, 269–70
  design example, 263
Crown wheel, 270
Crust-formed grinding-wheel, 237
Cup-drawing test, 325
Curing pressed material, 359
Current density, in spark erosion, 292
Curves, distribution, 385
Cut—
  depth of, 82–3
    and built-up edge, 60
  on shapers, planers and slotters, 174
Cutter heads, face milling with, 128
Cutter-grinding machines, 579–80
Cutters—
  gear, 274
  helical, 116, 118
  milling, 126–8
    for screw cutting, 230
  rack-type, 273
Cutting—
  gears, 272–83
    finishing processes, 283–9
  oxy-acetylene, 290

- Cutting—*contd.*
  - plunge, 499
  - screw thread, 229–31
- Cutting action, 1
- Cutting edge, twist drill, 146–8
- Cutting forces—
  - acting on single-point tool, 79–84
  - formulae for, 84
  - in turning, 20, 92–4
- Cutting fluids, 537–46
  - function of, 89
  - (*see also* Cutting oils)
- Cutting oils—
  - application of, 543–4
  - care and handling of, 548–50
  - effects on health, 546
  - for broaching, 167
  - methods of evaluating, 545–6
  - selection of, 544–5
- Cutting process—
  - effect of friction in, 62–3
  - effect of lubrication on, 63–4
  - mechanics of, 64–9
- Cutting resistance, on milling machine, 118, 120, 121
- Cutting speed, 82
  - and feed rates, 95
  - economical, 90
  - effect on built-up edge, 59
  - effect on tool life, 86–7
  - for broaching, 163
  - for hobbing, 280–1
  - for planing and shaping, 184
  - in turning, 94–6
  - of broaches, 167
  - of broaching machines, 170
  - of shapers, planers and slotters, 174, 177
  - permissible, 87
  - recommendations for, 89–90
  - ultrasonic machining, 220–1, 224, 225
- Cutting temperature, 69–71
- Cutting tools—
  - built-up edge and wear on, 59
  - single-point,.79–84
  - theory of, 51 *et seq.*
  - vibration of, 71–5
- Cutting velocity—
  - defined, 1
  - limits of, 3
  - optimum value of, 3
- Cylinder grinding machines, 205
- Cylinders—
  - measurement of bores of, 377
  - surface texture of aero-engine, 472–3
- Cylindrical furnace, vertical, 566
- Cylindrical grinding, 195–203
- Cylindrical ring gauges, 400–1
- Cylindrical slide, 32
- Cylindrical turning, 96–7

- DANGEROUS mechanisms, 598–600
- Deasphaltizing, 522, 523
- Dedendum, of gears, 249
- Deep drawing, load in, 339–41
- Deep-hole drilling machines, horizontal, 160
- Demulsibility, 529
- Depth gauges, 395–6, 401–2
- Depth micrometers, 401
- Design—
  - broach, 164–6
  - drilling jig, 503–6
  - examples of gear, 259–66
  - jig and fixture, 486–8
  - standardization and, 591–2
- Design department, 576
- Detergent additives, 524
- Development engineer, 578
- Deviation, standard, 385, 386, 387
- Dewaxing, 522, 523
- Diachenko, Professor P., 457
- Dial gauge, 370–1
- Diameter—
  - effective, 404
  - screw thread, 408
- Diameter-measuring machine, 374–5, 400, 404
- Diametral pitch of gears, 249
- Diametral shrinkage, 317–18
- Diamond pyramid hardness-testing mac ine, 398
- Diamond Pyramid Number, 398
- Diamond-dressed grinding wheel, 237
- Diamond turning, 476–8
- Diamond wheels, 188
- Die plate, 303
- Die radius, in flat-blank drawing, 324–5
- Diehead, for screw cutting, 229–30, 231
- Die-making, ultrasonic, 227
- Dies—
  - circular, for thread rolling, 232, 233
  - flat, for thread rolling, 232–3
  - forging, 303
  - screw-thread, 232
  - split, 336
- Dielectric—
  - effect of in spark erosion, 293
  - in spark erosion, 292 *ff.*
  - liquid, 291, 292, 293
  - for spark machining, 291, 292
  - spark erosion, 312
- Differential dividing, 140
- Differential thinning, 332
- Diffraction camera, electron, 421
- Dimensional inspection, 378
- Dimensional standardization, 592, 593
- Discharge circuit in spark machinery, 311
- Disintegrators, arc., 290–1
- Distance guards, 600, 608–9
- Distillation, fractional, 522
- Distillates, 522
- Distortion—
  - surface texture, 316, 429
    - photomicrographs, 414, 416
- Distribution curves, 385
- Dividing head, 405
  - milling machine, 136–43
  - optical, 371
- Double-action drawing, 353
- Double-action press, 345, 348–9
- Double helical gears, 267, 276–7
- Double-side double-crank press, 348
- Dovetail slideways, 32
- Down-cut milling, 128–30
- Draw beads, 320
- Draw key drive, 8, 11
- Draw-cut shapers, 177

Drawing-sheet-metal, 316 *ff.*, 342
  definition of, 316
  double-action, 353
  non-circular, 333–4
  principles of, 317–21
rawing ratio, 325–6, 333
rawing stores, 578
rawing tool, 356
ressing, abrasives for, 187
Drill bushes, 501–2
Drill plates, 503
Drilling—
  by spark machining, 292
  cutting oils for, 544
  deep-hole, 160
  equipment for spark erosion, 295 *ff.*
Drilling fixtures, 507
Drilling jigs, 501–6
rilling machines, 149–60
  design of, radial, 26, 28
rills, 144–9
  pole-change, 151
  ultrasonic, 221, 222–3
ives—
  feed, 16–22
  planing machine, 177–9
  power requirements of, 20–1
  rapid traverse, 132
  shaping, planing and slotting machine, 174
  spindle and feed, 1
Driving mechanisms, testing of, 44
Dropping-worm mechanism, 19–20
Duplex fixtures, 577
Dust and fume control, 610–11
ynamometers for measuring cutting components, 80

ARTH, decolourizing, 523
rthing, 611
onomics of machinery operations, 90–1
onomy of spark machining, 310
ge turning tool, 357
ucation in the factory, 618–21
fective diameter—
  screw plug gauge, 411
  screw thread, 408
ectric circuit for spark machinery, 294–5
ectric field in spark erosion, 292
ectric furnaces, 554, 556–8
ctric machining of metals, 290 *ff.*
ectric tools, portable, guards for, 609–10
ctrical methods of studying surface texture, 431
ectrical muffle-type furnaces, 571
ectrode materials, spark machining, 300
ectrodes, tool, 290, 292, 293, 298, 303 *ff.*, 312, 313
lectrolytic grinding, 315
ctrolytic methods of finishing gears, 288
ectrolytic polishing, 315
ectro-mechanical drives for broaching machines, 170
ectromagnetic forces in spark erosion, 292
ctron diffraction camera, 421
ctron microscope, 419, 448–9
ctronic controls, machine tool, 174
ctronic guards, 609
ctrostatic forces in spark erosion, 292

Elements, heating, 556
Embossing, 342
  by the drawing process, 335–6
Embossing tool, 353
Emery, 187
Emulsified cutting fluids, 539–40
Emulsified pastes, 540
Emulsifiers, 524
End milling, 275
End standards of length, commercial, 362–7
Engineering—
  elements of production, 574–90
  safety, 611–12
Engler viscosity instrument, 551
Engraving equipment for spark-erosion, 295 *ff.*
Envelope system, 450
Epicyclic gears, shaving, 285
Ericksen test, 320, 325
Erosion, spark, *see* Spark machining
Essential Works Order, 621
Esters, synthetic, 527–8
Explosion, danger from, 610
External grinding, 192
  speed of traverse, 194
Extreme pressure additives, 524
Extreme pressure lubrication, 520–2
Extreme pressure oils, 538, 539, 541–3

FACE milling, 128
Face width of gears, 249
Factory Acts, 597, 598, 618
Factory administration, 575
Factory layout, planning, 580, 582–3
Failure, fatigue, 485
Fatigue failures, 485
Fatty acids, 523
Fatty oils, 523, 538, 541
Faxfilm process, 468
Feed—
  depth of cut and, 82–3
  drilling, 148–9
  factors limiting, 90–1
  of shapers, slotters and planers, 174, 177
Feed drives, 16–22
Feed movements, 16–17, 18–19
Feed rate—
  and cutting speeds, 95–6
  measurement of, 17–18
Fencing, 597–8
Fiducial indicator, 372
Films, lubricant, 519–20, 521
Filters, oil, 547, 548
Fine surfaces, application of, 482–5
Finish, surface, ultrasonic machining, 227
Fire, danger from, 610
Fire point, lubricating oil, 550
Fire-fighting equipment, 312
Fit systems, 382, 383
Fits, 378–83
  clearance, 380
  interference, 380
  slide, 381
  transition, 381
Fixed-bed milling machines, 135–6
Fixed head crank shaper, 174–6
Fixed guards, 600, 602–4
Fixtures—
  broaching, 510–2

Fixtures—*contd.*
  drilling, 507
  duplex, 577
  horizontal boring machine, 509–10
  jigs and, 486–512
  milling, 506–7
  turning and boring, 507–9
Flake graphite, 526
Flame-proof apparatus, 611
Flank, screw thread, 408
Flank angles, screw thread, 408, 409
Flash point, lubricating oil, 550
Flat, toolmaker's, 368
Flat slide, 30, 32
Flow planning, 583
Flow type chips, 54–5, 57
  plastic deformation of, 65
Fluid, minimum requirements of hydraulic, 535
Fluid lubrication, 515–19
  requirements for good, 516
Fluids, cutting, 537–46
Fluon, 528
Flutes of taps, 238–40
Flypress, 344, 346–7
Flywheel of press, 344, 345
  of single-action, 347–8
Foolproofing of jigs and fixtures, 488
Force—
  blank-holding, 321
  blanking, 337
  friction, 513, 515, 516
  in deep drawing, 339, 340, 341
  in mechanical press, 345
  ironing operation, 331
  wedging, 400
Force-feed lubricators, 547
Forced air circulation furnaces, 561–3
Forces—
  component in turning, 20
  cutting, acting on single-point tool, 79–84
  cutting, in turning, 92–4
  formulae for, 84
Forging, hot press, 359
Forging dies, 303
Fork gauges, 401
Form machining, difficulties of anodic, 315
Form milling of gears, 275–6
Form tool, taper turning, 100, 101
Forming, 342, 347
  by the drawing process, 334–7
Forming tool, 356
Formulae, gear, 251–3
Forward planning, 580, 582–3
Fouling piece, 488
Fractional distillation, 522
Frazer end-milling machine, 576
Free drawing, 317–19
Frequency, induction heating, 559
Friction, 513–14
  cause of need for cutting fluids, 537
  effect of in chip formation, 62
Friction coefficient, 63
Friction drives, 11
Friction losses, 516–17
Friction-disc sawing, 290
Frictional force, 515, 516
Full film lubrication, 515
Full form screw plug check gauge, 404
Fume, dust and, control, 610–11
Funnel, pressure sinking a, 333
Furfuraldehyde, 523
Furnaces—
  classification by temperature, 561–4
  electric, 554, 556–8
  gas, 554
  high-temperature, 571
  low temperature, 561–3
  medium temperature, 564–71
  very high temperature, 571–3

GAP gauges, 385, 392, 394–5
  plain, 411
Gap of light method, 398, 401
Gas carburizing, 556
Gas furnaces, 554
Gas-fired furnaces, 571
Gasoline, 523
Gauge tolerances, 391–3
Gauges, 376–7, 577
  adjustable, 392
  bar, 389
  Bourdon pressure, 377
  calliper, 396, 409, 411
  check, 405
  cylindrical ring, 400–1
  depth, 395–6, 401–2
  dial, 370–1
  for small tolerances, 385
  form, 401
  gap, 385, 392, 394–5
  "Go", 389, 391, 392, 394, 395, 396, 397, 399, 405, 409, 411
  height, 401–2
  limit, 389–91, 394–8
  measurement of limit, 394–405
  "Not Go", 389, 391, 392, 394, 396, 397, 399, 405, 411,
  parallel, 399
    gap, 399
    screw plug, 403, 404
    screw ring, 404–5
  pin and bar, 394
  plain gap, 411
  plain plug, 389, 392, 394, 399–400, 411
  plug check, 404
  position, 398, 405
  profile, 396–7, 401
  ring, 385, 392
  screw, 396
  screw plug, 411
  screw ring, 409, 411
  screw-thread measuring, 245
  sensitive dial, 402
  slip, 362–4, 392, 393, 399
  taper, 397
  taper plate, 402
  taper plug, 402
  taper ring, 403
  vernier height, 370
Gauging, control by, 389 *ff.*
Gauging surfaces, testing, 398–9
Gauging systems, limit, 393–4
Gauging systems for screw threads, 409–11
Gaussian curve, 385, 386
Gear cutting, 272–83
  cutting oils for, 544
  finishing processes, 283–9

Gear grinding, 285–7
Gear lapping, 287–8
Gear ratio, 249
Gear shaving, 283–5
Gear teeth—
  phosphate coating of, 289
  shot peening, 289
Gears, 246–72
  automotive gear-box, 281–2
  caliper settings for, 257–8
  definitions relating to, 246–51
  design of, examples, 259–66
  formulae relating to, 251–3
  hobbing, 277–82
  interference, 253–7
  lubrication of, 533–4
  P I V, 16
  shaping, 276–7
  shot-blasting, 288
  types of, 266–72
General-purpose drilling machines, 151–2
Generating instruments, surface texture, 433–8
Generator, spiral bevel-gear, 283
Geometry, surface finish and, 475–6
Glass, abrasives for grinding, 187
Glycerides, 523
Glycerol, 525
“Go” gauge, 389, 391, 392, 394, 395, 396, 397, 399, 405, 409, 411
“Go” plug check gauges, 365
“Go” ring-gauge, 365
Grain structure, in screw cutting, 232
Graphite, as lubricant 521, 526
Graphs
  of component production, 385
  of surface texture, 417, 418
Greases, 525
  care and handling of, 548
Grinding, 186–217, 478–80
  centreless, 209–12
  concentric, 211
  cylindrical, 195–203
  effect on surface texture 418
  electrolytic, 315
  gear, 285–7
  internal, 192, 203–6
  plain, on centreless machine, 209
  screw thread, 245
  speed of traverse in, 194–5
  speed of wheel and work, 189–93
  spline, 212–13
  thread, 236–8
  through-feed, 210
  tool, 579–80
  ultrasonic, 218
  work steadies for, 195, 200–3
Grinding machines—
  adaptation for spark machining, 310–12
  alignment of, 214–15
  automatic internal, 205–6
  bed design for, 24
  checking, 215
  cylinder, 205
  slideway, 208–9
  spindle bearings of, 215–16
  surface, 206–9
  universal, 213–14
Grinding times, calculation of, 216–17
Grinding-wheels, 186–9
  composition of, 187–8
  for thread grinding, 236–7
  formed, plain grinding with, 202–3
  of centreless machine, 209–10
  saucer type, 208
  speeds of, 189–93
  structure of, 188
Grindstones, 187
Grits, 187–8
Grooves, oil, 530–1
Group standardization, 593–4
Gun-nosed tap, 239

HALOGENO-HYDROCARBONS, 528
Hand micrometer, 371
Hand scraping, 483
Hand-press, 346–7
Handling, materials, 583–4
Hardness, of gauging surfaces, 398
Hardness-testing machine, 398
Head—
  dividing, 136–43
  drilling, 152
  optical dividing, 371
Health aspects of cutting oils, 546
Heat treatment appliances, 554–73
Heating, induction, 558–61
Heating systems, 554, 556–61
Height gauges, 401–2
  vernier, 370
Heinrich, H. W., 597
Helical gears, 267–9
  blank diameters of, design example, 262
  crossed, 269–70
    design example, 263
  design example, 259–60
  hobbing, 279–80
  planing, 273–4
  shaping, 276–7
  shaving, 284–5
Helicoidal worms, involute, 287
Helicoids, involute, 267
Helix angle of gears, 249
Helix, base, of gears, 249
Helix lead, 250
High-pressure air gauging, 377
High-temperature furnaces, 571
High-temperatures, greases for, 525
Higher Management, 625
Hobbing, gear, 277–82
Hobs, 278–9
Hobs, worm gear, 280
Hole basis system of fits, 381
Holes, trepanning rectangular, 292
Honeycomb sandwiches, cutting light metal, 292
Honing, 480–1
Hoop compression, in flat-blank drawing, 322
Hoop compressive stress, 318, 319
Hoop dimension, 317
Hook angle of broach teeth, 165
Hook tap, 241
Horizontal boring machine fixtures, 509–10
Horizontal broaching machines, 169–70
Horizontal comparators, 374, 401
Horizontal milling machines, 132
Horizontal projectors, 376

Hot pressing, 359–60
Human relationship, in factories, 588–9, 613–25
Hydraulic bulging, 336
Hydraulic fluid, minimum requirements of, 535
Hydraulic gears, 11, 14, 16
Hydraulic press, 344, 359–60
Hydraulic systems of lubrication, 535–6
Hydrocarbons in lubricants, 520
Hydrodynamic lubrication, 430, 515
Hypoid gears—
  lapping, 287
  phosphate coating of, 289

IMPERIAL standard yard, 361, 362
Index plates, in dividing heads, 140–3
Indexing table-type drilling machine, 156–8
Indicator, fiducial, 372
Induction heating, 558–61
Industrial justice, 621–2
Industry, a system of co-operation, 614–15
Inserts, broach, 166–7
Inspection, 378 *ff.*
Instruments
  calibration of surface texture measuring, 441–3
  use of stylus, 463–6
Interchangeability, 574–5
  of components, 378, 385
Interference fits, 380
  surface texture and, 474
Interference method of assessing surface texture, 443–8
Interlock guards, 600, 605–6
Intermolecular attraction, 364
Internal broaches, 168
Internal grinding, 203–6
  speed of traverse, 194
Internal grinding machines—
  automatic, 205–6
  checking, 215
International Federation of National Standardizing Associations, 383 fn.
International prototype metre, 361, 362
Involute curve, 246 *ff.*, 253
Involute gears, 246 *ff.*
  shaping, 276
Involute helicoidal worms, 287
Involute helicoids, 267
Iron chloride films, 521
Ironing, 317, 331–2
Irregularities, measurement of surface, 452–6

JACKS—
  for milling fixtures, 488–90
  spring-loaded, 497
Jigs, drilling, 501–7
Jigs and fixtures, 486–512
Jigs and tool department, 576
Johansson, C. E., 362
Johnson, C., 566
Joint consultation, 617–18
Journal bearing, lubrication of, 517–18
Journals, grinding, 201
Justice, industrial, 621–2

KARDEX recording system, 578
Keep plates, 494, 495
Kerosene, 523
Kinetic friction, 513, 535
Knee-type milling machines, 130, 132, 135

LAND, broach tooth, 165
Lap-cylinders, 245
Lapping—
  by anodic machinery, 314
  gear, 287–8
  ultrasonic methods of, 218
Lard oil, 523
Lathe—
  adaptation for spark machinery, 310–12
  bed, 23–4
  centre, tool life on, 94
  screw-cutting in, 229 *ff.*, 244
Lauric acid, 523
Lead, helix, 250
Lead angle, 250
Lead poisoning, 610
Leadership in industry, 623–5
Leadscrew-nut mechanism, 19
Length—
  commercial end standards of, 362–7
  national standards of, 361–2
  sampling, 452–6
  traversing, 453
Length bars, 364–5, 399
  accessories for, 365–7
Levelling for acceptance test, 45
Lewis, C. R., 442
Light-section method of surface texture measurement, 448
Lime-base greases, 525
Limit gauges, 389–91
  measurement of, 398–405
  types and uses of, 394–8
Limit gauging, 378
  systems, 393–4
Limits, control, 386, 387, 388
Limits and fits system, 383,
Limits, fits and tolerances, 378–83
Limits of size, 380
Line of contact, gears, 250
Line standards, 361–2
Linnik, Professor, 444
Lip angle, 146, 147
Lip clearance, 146
Lithium-base greases, 525
Live spindle workhead, 198, 199, 205
Load—
  broaching machine, 171–2
  clamping, 492
  in blanking operations, 337–9
  in deep drawing, 339–41
  ironing, 332
  punch, 331
    in flat-blank drawing, 322–4
  re-drawing, 330
Loading of spindles and bearings, 37–8
Lobing of gauge, 400
Losses, friction, 516–17
Low temperature furnaces, 561–3
Lubricants—
  care of, 547–50
  coolants as, 167
  effect on built-up edge, 60
  for cold pressing, 358–9

Lubricants—*contd.*
  method of application, 536–7
  methods of evaluating, 545–6
  solid, 521
  special, 525–8
  tapping, 243–4
  types of, 522–8
Lubricating compounds, 358–9
Lubricating oils—
  care and handling of, 547–8
  properties of, 550–3
Lubrication—
  boundary, 519–20
  effect in cutting process, 63–4
  effect of on tool material, 83–4
  effect on surface roughness, 77
  extreme pressures, 520–2
  hydraulic systems of, 535–6
  hydrodynamic, 430
  in gear lapping, 287
  of cutting tools, 537 *ff.*
  of machine tools, 38, 41
  requirements for good fluid, 516
  theory of, 515–22
Lubricators, care of, 547

MACHINE loading section, 578
Machine tools—
  acceptance tests, 45–50
  control devices, 41–2
  design, 22 *et seq.*
  efficiency of, 38
  fundamentals of elements, 22 *ff.*
  lubrication of, 38, 41, 528–33
  manufacture of, 43 *ff.*
  operation of, 41–2, 43
  performance, 21 *ff.*
    checks of, 49–50
  principles of design, 1 *ff.*
  setting of, 41–2, 43
  testing alignment of, 42–9
Machined surfaces—
  characteristics of, 60–2
  roughness of, 75–9
  topography of, 416
Machining—
  anodic, 313–15
  arc, 290–1
  electric, of metals, 290 *ff.*
  irregularities produced by, 416
  spark, 291–313
  ultrasonic, 217–28
Machining operations, economics of, 90–1
Machining time, 18
Machines—
  boring, fixtures for horizontal, 509–10
  broaching, 169–72
  diameter-measuring, 374–5, 404
  drilling, 149–60
  for screw-thread cutting, 233–4
  hardness-testing, 398
  grinding, 195 *ff.*
  helical-gear planing, 273–4
  hobbing, 282
  measuring, 385
  milling, 116–43
  multi-gauging, 411
  pitch-measuring, 375–6
  planing, 173, 177–80, 183–5
  preparation of fine surfaces by, 475–85
  shaping, 173–6, 183–5
  slotting, 173, 180–3, 183–5
  Sigma sorting, 412
  tool grinding, 579–80
  universal grinding, 213–4
Magnesium, broaching, 167
Magnetic oil filters, 548
Magnetostriction, defined, 217
Magnification, standard, 401
Magnifying devices for surface texture errors, 431
Manchester College of Technology, 473
Mandrels, danger from revolving, 598
Manometer, 377
Manual lubrication, 536
Manual on Cutting of Metals, 84
Mass production, 378
Material control, 578
Materials—
  abrasive, 187–8
  cutting speeds for various, 184
  machined, 60–2
  ultrasonic cutting speeds in various, 224. 225
  ultrasonic machining of, 219–20
  workpiece, for lathes, 110–11
Materials handling, 583–4
Mating threads, 408–9
Mean-line measures, 449–50
Measuring block, universal, 405
Measuring equipment, 367
Measuring machines, 385
Measurement—
  control of size by, 385
  effect of temperature on, 367
  equipment for, 367–77
  of limit gauges, 398–405
Measurement of surface texture, 413 *ff.*
  comparison of methods, 456–63
  kinds of, 449–52
Measurement standards, 361 *ff.*
Measures—
  crest line surface, 450, 452
  mean line surface, 449–50
  peak-to-valley surface, 449
Mechanics, presswork, 343–6
Mechanisms, dangerous, 598–600
Medium-temperature furnaces, 564–71
Mercurial poisoning, 610
Metal drawing, sheet, 316 *ff.*
Metallic soaps, 358, 520, 525
Metallographic technique, 53
Metallurgical microscope, 419
Metals—
  effect of spark erosion on, 293–4
  electric machining of, 290 *ff.*
  non-ferrous, cutting, 290
  ultrasonic cutting speeds in, 225
Method study, 585–6
Methods engineer, 576
Metre, international prototype, 361, 362
Metric screw threads, 406
Mica, 527
  as lubricant, 521
Michelson interferometer, 444
Micro-interferometer, 444, 447
Micrometers, 371–3
  bench, 400, 401

Micrometers—*contd.*
  depth, 401
  hand, 399, 400
  screw-thread, 375
Microscope—
  electron, 419, 448–9
  in assessing surface texture, 418–21
  metallurgical, 419
  optical, 418–9
  surface finish, 447
  toolmakers', 376, 401
Microwelding, 514
Milling—
  cutting fluids for, 545
  form, of gears, 275–6
  of spiral bevel gears, 282–3
Milling cutter, screw cutting by, 230
Milling heads, 136
Milling fixtures, 488–501, 506–7
  general construction, 497–501
Milling machines, 130–6
  design, 24, 26
  loading conditions, 118
Milling operations, slab, power requirements of, 20
Milling process, 116–30
Mineral oils, 520, 522–3, 538, 541
Mixed-base greases, 525
Modulated carrier instruments, surface texture, 431–3
Module, gear, 250
Molecules of lubricants, action of, 520
Molybdenite as lubricant, 526
Molybdenum, use in furnaces, 573
Montgomery, Lord, 624
Morale in industry, 623–5
Morton, F. J. Burns, 622, 623
Motion, slotted link, 175–6
Motor, hydraulic, 14
Motor-car bodywork, 351
Movable hearth furnace, 564–5
Muffle-type furnaces, electrical, 571
Multi-gauging machines, 411–12
Multi-point clamping, 494
Multi-purpose greases, 525
Multi-spindle automatic lathes, 113–15
Multi-spindle drilling machines, 153–5
Multi-stage drawing, 331–3
Multiple-thread milling, screw-thread, 245
Multiple-thread milling cutter, 230, 231

NATIONAL Institute of Industrial Psychology, 624
National Physical Laboratory, 364, 367
Necking, drawing process, 336–7
Negative rake tap, 240–1
Nelson, D. R., 448
Neutralization value, 552
Newton, Sir Isaac, 515
Non-circular drawing, 333–4
Non-circular turning, 107
Normal distribution curve, 385
Normal running fit, 381
Norton gear, 8, 11
Nose radius of cutting tool, 88
"Not Go" gauge, 389, 391, 392, 394, 396 397, 399, 405, 411
'Not Go" plug check gauges, 365
Numerical aperture, 419
Nuts—
  perfect, 408, 409
  threading of, 241–2
  tolerance of, 406

OBLIQUE cutting operation, 52
Obliquity, angle of, 52
Oil circulation systems, maintenance of, 547
Oil grooves, 530–1
Oil-base cutting fluids, 540–3
Oil-in-water dispersions, 525
Oil-mist lubrication, 533
Oil-type cutting fluids, 41–3, 538
Oiliness additives, 524
Oiliness of lubricants, 520
Oils—
  care and handling of lubricating, 547–8
  colour of, 553
  compounded, 523–4
  lubricating, 520, 523–5
  soluble, 538–40
  sulphurized fatty, 521
  transformer, as dielectric, 293
Oilstone test, 463
Open side planing machine, 179
Optical dividing head, 371
Optical microscope, 418–19
Optical projection, 376, 401
Orders, giving, in factories, 622–3
Orthogonal cutting, 51–2, 67
Oscilloscopes, cathode-ray, 296
Output, performance of, 44
Oxides, lubricants and, 514
Oxy-acetylene cutting, 290

PAD, swivelling, 424 *ff.*
Palmitic acid, 523
Paper sizes, metric standardization of, 592
Paraffin as dielectric, 293
Paraffin wax, 523
Parallel gap gauges, 399
Parallel screw plug gauges, 402, 404
Parallel screw ring gauges, 404–5
Parallelism tests, machine tool, 48
"Pass over" thread grinding, 236, 237
Pastes, emulsified, 540
Pattern in surface texture, 413
Peak-to-valley measures, 449
Penetration control, automatic, 296
Peasky Martens method, 550
Perfect bolt, 409
Perfect nut, 409
Perforating, 342
Performance, check for machine tool, 49–50
Periphery grinding wheel, 192, 194
Personnel management, 615–17
Personnel officer, 575
Personnel policy in workshops, 615–17
Petroleum crude oils, 522
Phosphate coating of gear teeth, 289
Photo-electric guard devices, 609
Pieces, setting, 497
Piercing, 342, 347
  ultrasonic, 218, 219, 227
Piezo-electric devices, surface texture, 435–437

Pillar-type shaper, 175, 176
Pin gauges, 394
Pit furnace, 566
Pitch—
  axial, of gears, 249
  broach teeth, 165
  diametral, of gears, 249
  normal base, 250
  of gears, 250
  of parallel screw plug gauge, 404
  transverse, 251
    base, 251
Pitch angle, of gears, 250
Pitch circle, 250
Pitch diameter, gear, 247
  virtual, 255
Pitch error—
  method of determining, 48–9
  of screw threads, 409
Pitch point, 250
Pitch-measuring machine, 375–6, 404
P.I.V. gear, 16
Plain bearings, lubrication of, 529–32
Plain gap gauge, 411
Plain grinding, 195–203
  on centreless machine, 209
  with formed grinding-wheel, 202–3
Plain grinding machine, checking, 215
Plain limit gauges, 385
Plain plug gauges, 389, 392, 394, 399–400, 411
Plain angle of cutting tool, 88
Planing machines, 173, 177–80, 183–5
  characteristics of, 173–4
  helical-gear, 273–4
  power requirements of, 21
Planing spur and helical gears, 273–4
Planishing, in drawing process, 335
Planning, forward, 580, 582–3
Plano-milling machines, 136
Plant engineer, 575
Plastic deformation, 60, 61, 65
Plastic flattening, 514
Plastic flow in materials, 316, 318
Plastic flow of metals, 329
Plate gauges, taper, 402
Plates—
  drill, 503
  index, in dividing heads, 140–3
  keep, 494, 495
  milling fixture profile, 490–1
  surface, 367–8
Ploughing, 77
    frictional force component, 514
Ploughing forces, 62
Plug check gauges, 404
Plug gauge—
  parallel screw, 402, 404
  plain, 389, 392, 394, 399–400, 411
  screw, 411
  taper, 402
Plug tap, 242
Plunge cutting, 499
Plunge grinding, 194–5
  screw-thread, 236, 237
Plunge rolling, screw-thread, 234–5
Pneumatic blank-holder, 321
Polar charts of roundness deviations, 428–9
Polar diagram of bearing, 518
Pole-change drills, 151
Polishing, 482
  electrolytic, 315
  ultrasonical method of, 218
Polyalkylene glycols, 528
Polymerizing, 359
Position gauges, 398, 405
Position of safeguards, 600, 602
Pour point, 552
Pour point depressants, 524
Power requirements—
  of drives, 20–1
  of milling machine, 120–2
  spark erosion, 298
Power-weight ratio, 574
Precision grinding machines, 189
Precision slotting machines, 180
Press—
  hydraulic, 359–60
  inclined, 346
  mechanical, 344
Press tools, 352–7
Pressing, 342 *ff.*
  cold, 356–7
  hot, 359–60
Pressure—
  blanking, 344
  blank-holding, 345
  clamping, 320–1
Pressure angle—
  normal, of gears, 250
  transverse, 251
Pressure blank-holder, positive, 321
Pressure exerted by crank press, 344
Pressure gauge, Bourdon, 377
Pressure lubrication, extreme, 520–2
Pressure sinking, 332–3
Presswork, 342 *ff.*
  choosing the right machine, 351
  mechanics of, 343–6
  planning operations for, 352–7
Primary texture, 416
Probability, theory of, 385, 387
Process engineer, 576, 578
Process lay-out, 576
Processing, assembly, 585
Production—
  graph of component, 385
  mass, 378
  speed of, 22
  steps to, 576–8
Production controller, 575
Production engineer, 574, 575
Production engineering, elements of, 574–90
Production slotting machines, 180, 183
Prolific gauges, 396–7, 401
Profile plates, milling fixture, 490–1
Profile turning, 105–7
Profilometer, 433, 434
Progressive tooling, 356
Projection, optical, 376, 401
Propane, 523
Properties of cutting fluids, 537–8
Properties of lubricating oils, 550–3
Protractors, vernier, 371
Puckering, 319–20, 321
Pull-head of broaching machine, 170
Pull-type broaches, 164
Pump, oil delivery, 14
Pump systems of lubrication, 536–7

Punch—
  double-action press, 348
  hemispherical, 328
  rubber-headed, 336
Punch load, 331
  in flat-blank drawing, 322–4
Punch radius, in flat-blank drawing, 325
Puncher slotting machines, 180
Pure drawing, 317
Push-type broaches, 164
Pusher type furnaces, 568

QUALITY control, 378, 385–405
Quenching, induction heating, 560–1
Quick-return motion, Whitworth, 176

RACK, basic, of gears, 249
Rack-and-pinion drive, 19
Rack press, 344
Rack-type cutters, 273
Radial cutters, 229
Radial drilling machines, 152
Radial tap, 241
Radial tensile stress, 319
Radiant tubes, 558
Radioactive materials, 611
Radio-isotopes in surface texture measurement, 470
Radius—
  corner, in drawing, 333, 334
  die, in flat-blank drawing, 324–5
  of broad teeth, 166
  of rolling circle, 456
  punch, in flat-blank drawing, 325
Rail planing machine, 179
Raising, single-action, 353
Raising tool, 353, 356
Rake angle, 83
  effect on built-up edge, 60
  effect on surface roughness, 76
  effect on tool wear, 88–9
  in screw cutting, 230
  of taps, 238
Rake of broach teeth, 165
Rake tap, 241
Ram, shaping machine, 174, 175, 176, 177
Ramsbottom test, 553
Range of sizes, 387
Rape oil, 523
Ratefixing department, 578
Rates, cutting, with ultrasonic machines, 222
Ratio drawing, 325–6
Reaction slides, broach, 167
Reciprocating tools, advantage of, 217
Recreational schemes, 618
Re-drawing, 326–31
Reduction, degree of in re-drawing, 326–7
Redwood viscosity instrument, 551
Reference circle, of gears, 250
Rejects, 378
Relaxation circuit, 294
Relaxation method of estimating temperature distribution, 71
Relief, broach teeth, 165
Replicas of surface textures, cast, 468–9
Reservoir systems of lubrication, 536
Residual oils, 523
Resinoid grinding wheels, 188, 189
Resistance, spark machining circuit, 294–5
Resistors, electric furnace, 557
Revolving parts, danger from projections from, 599
Reynolds, Osborne, 516
Rigid stops, 19
Ring gauges, 385, 392
  cylindrical, 400–1
  parallel screw, 404–5
  screw, 409, 411
  taper, 403
Roll grinding machines, 203
Rolled plates, British Standards for, 595–6
Roller hearth furnaces, 568
Roller type gauges, 396
Rolling, thread, 229, 231–6, 238
Rolling bearings, lubrication of, 532–3
Rolling circle, radius of, 456
Roof panel, motor-car, 343
Root, screw thread, 408
Root circle, of gears, 251
Rotary drum furnaces, 570–1
Rotary hearth conveyor furnaces, 569–70
Roughness, surface, 464
Roughness specimens, standard, 466, 468–9
Rubber bonded grinding wheels, 188
Rubber-headed punch, 336
Rules, works, 617, 622
Running, test for true, 47
Running fit, 381

SAFETY and accident prevention, 619
Safety devices, 597–612
Safety engineering, 611–12
Safeguarding, principal methods of, 600–9
Salt bath furnace, 563, 566, 571
Samples, production, 387
Sampling length, 452–6
Saponification value, 553
Saucer-type grinding wheel, 208
Saw, anodic, 314
Saw diagram, 4
Sawing—
  by anodic machining, 313
  friction disc, 290
Saybolt viscosity instrument, 551
Schlesinger test chart, 45, 46
Scrap metal, 343
Scratch marks, 464
Screw gauges, 396
Screw plug gauge, 411
  parallel, 402, 404
Screw ring gauge, 409, 411
  parallel, 404–5
Screw-thread micrometer, 375
Screw threads, 105, 405–9
  elements of, 408
  factors influencing quality of, 230–1
  gauging system for external, 409–11
  gauging system for internal, 411
  inspection and measurement, 245
  pitch errors, 409
  production of, 229–45
Screws and bolts, British Standards for, 594
Second tap, 242
Secondary texture, 416
Segmental tools, 303
Selective assembly, 384–5
Sensitive dial gauge, 402

Sensitive drilling machines, 149, 150–1
Sentinal "Cri-Dan" screwing machine, 576
Servo-mechanism, 312
Servo-systems, tool rotating, 296
Setting pieces, milling fixture, 497
Setting up centreless grinding machine, 211
Shaft basis system of fits, 383
Shafts, danger from revolving, 598
Shaker hearth furnace, 568–9
Shaping gears, 276–7
Shaping machines, 173–6, 183–5
  characteristics of, 173–4
  hydraulic, 177
Shaving gears, 283–5
Shear angle, 55, 57, 66
Shear plane, 55
Shear type chip, 54, 57
Sheet-metal drawing, 316 *ff.*
Sheet-metal fabrications, 343 *ff.*
Shellac bonded grinding wheels, 188
Shoe, 424 *ff.*
Shot blasting, 482
  gears, 288
Shot peening gear teeth, 289
Shrinkage, hoop, 318
Shrinking, diametrical, 317–18
Sick clubs, 618
Sigma microtest, 435
Sigma sorting machine, 412
Silicate bond, 188
Silicon carbide, 187
Silicon dioxide, danger to health of, 610
Silicones, 525
  as lubricants, 527
Sine bar, 371
Single-action press, 345, 347–8
Single-action raising, 353
Single-point cutting tool, 244
Single-ribbed milling cutter, 230, 231
Sinking, pressure, 332–3
Size—
  control of by measurement, 385
  limits of, 380
Skid, 424 *ff.*
Slack running fit, 381
Slide fit, 381
Slides, broach reaction, 167
Slides of double-action press, 345
Slideway grinding machines, 197, 208–9
Slideways—
  effect on machining, of imperfect, 416
  lubrication of, 534–5
  machine tool, 28–32
Sliding, 514
  hydrodynamic, 516
Sliding gear devices for drives, 8
Slip-gauge, 362–4, 392, 398, 399, 401
Slip-gauge accessories, 365–7
Slip gear, 8
Slotted link motion, 175–6
Slotting machines, 173, 180–3, 183–5
  characteristics of, 173–4
Slurry, feed of in ultrasonic machinery, 224
Smoothness, 475
Snagging, abrasives for, 187
Soaps, metallic, 358, 520, 525
Soaps as lubricants, 520, 521
Social schemes, 618
Soda-base greases, 525
Sodium soaps, 525
Solex Company, 377
Solid lubricants, 521
Soluble oils, 524–5, 538–40
Solvent refining, 522, 523
Sorting machine, Sigma, 412
Spalling, 85
Spark erosion, *see* Spark machining
Spark machining, 291–313
  economics, of, 310
  equipment for, 294–8
  technology of, 298–313
Spark-toughening, 292
Specific gravity, 553
Specification of surface texture, 461–2
Speed, cutting, 82
  drilling, 148–9
  effect on surface roughness, 76
  for hobbing, 280–1
  for planing and shaping, 184
  for screw-cutting, 230
  in turning, 94–6
  of broaches, 163, 167
  of grinding-wheel, 189–93
  of shapers, planers and slotters, 174, 177
  recommended, 89–90
  ultrasonic, 220–1, 224, 225
Speed diagrams, 11
Speed-change mechanisms, 7–16
Speed of traverse in grinding, 194–5
Spindle—
  machine tool, 32–8
  tests for, 47–8
Spindle bearings, grinding machine, 215–16
Spindle drives, 1
Spindle speeds—
  arithmetical progression of, 4
  geometrical progression of, 5, 7
  in surfacing, 97–100
  logarithmic progression of, 5
  of workpiece or tool, 1
  optimum, 3
Spindles, danger from revolving, 598
Spiral bevel gears, 270–1
  lapping, 287
  milling, 282–3
Spline grinding, 212–13
Splined bores, 511
Split die, 336
Spur gears—
  design example, 259
  hobbing, 279
  planing, 273
  shaping, 276
  shaving, 284–5
  straight tooth, 266–7
Spragg, R. C., 470
Square threads, 406
Stamping, 342 *ff.*
Stampings, 348, 349, 351, 357–8
Standard deviation, 385, 386, 387
Standard magnification, 401
Standardization, principles of, 591–6
Standards—
  line, 361–2
  of angle, commercial, 367
  of length, commercial end, 362–7
  of length, national, 361–2
Static friction, 513

Steadies, work, for grinding, 195, 200–3, 209
Stearic acid, 520, 523
Steel—
  coolants for broaching, 167
  effect of spark erosion on, 294
  electric spark toughening of, 312–13
  machining by electricity, 291–2
  mild, broaching, 167
  mild, in cold pressing, 351
Steel straightedges, large, 369
Stick-slip, 514, 535
Still thread, 237
Stopping mechanisms for feed-driving devices, 19
Stops, fixture clamp, 496
Storekeeper, 579
Straight bevel gears, 270
Straight land, 165
Straightedges, 368–9
Strainers, oil, 547
Stress—
  compressive, 62
  tensile, 331
Stresses—
  effects of ultrasonic machining, 226
  in clamped drawing, 317
  in spark-machined metal, 294
  residual, 62
Stretching, in sheet metal drawing, 320
Stubbing, 255
Stylus, 421–2
Stylus instruments, use of, 463–6
  in surface texture measurements, 421–431
Suggestion schemes, 618
Sulphide films, 521
Sulphochlorinated cutting oils, 543
Sulphur dioxide, liquid, 523
Sulphurized cutting oils, 167, 541–3
Sulphurized fatty oils, 521
Super-finishing worm-threads, 288
Supersensitive drilling machines, 149, 150
Surface, numerical assessment of, 449–63
Surface assessment in the workshop, 466, 468–75
Surface broaches, 166–7
Surface broaching, 168–9
Surface broaching machine, 170
Surface distortion, 316
Surface finish, ultrasonic machining, 227
Surface grinding, 192
  speed of traverse, 194
Surface grinding machines, 206–9
  checking, 215
Surface micro-interferometer, Hilgar and Watts, 444
Surface finish microscope, 447
Surface friction, heat generated by, 537
Surface measures, comparison of methods, 456–63
Surface plate, 367–8
Surface roughness—
  built-up edge and, 59
  effect of change of tool material on, 77–9
  effect of lubrication on, 77
  effect of rake angle on, 76
  ideal, 76, 78–9
Surface texture—
  cast replicas of, 468–9
  functional aspects of, 469–75
  geometry and finish of, 475–6
  machine finishing methods, 475–85
  measurement of, 413 *ff.*
  topographic assessment of, 419–49
Surfaces—
  application of fine, 482–5
  testing gauging, 398–9
"Surfagage", 437
Swivel clamp, 492
Swivelling pad, 424 *ff.*
Symbols, bevel gear, 249–51
Synthetic esters, 527–8
Synthetic lubricants, 527–8
Système Internationale screw threads, 406
Systems—
  gauging, for screw threads, 409–11
  heating, 554, 556–61
  limits and fits, 383
  lubrication, 536–7

TABLE-TYPE, indexing, drilling machine 156–8
Tackinses additives, 524
Tailstock—
  off-set, for taper turning, 100, 101–3
  tests of, 48
Talc, 527
  as lubricant, 521
Talyrond instrument, 428, 430, 480
Talysurf instrument, 423, 426, 431, 433, 436, 478
Tandem planing machine, 179
Tangential cutters, 229
Tantalum, use in furnaces, 573
Taper attachment, 100, 103–5
Taper gauges, 397
Taper plate gauges, 402
Taper plug gauge, 402
Taper ring gauge, 403
Taper section, surface texture measurement, 448
Taper tap, 242
Taper turning, 100–4
Tapping—
  cutting oils for, 544
  data, 243–4
  factors in effective, 242–3
  screw-thread, 238–44
    ultrasonic method of, 218
Tapping reverse, 155–6
Taylor-Hobson Laboratory, 470, 473
Taylor's principle, 389
Tear type chip, 53
Technology, spark erosion, 298
Teeth—
  broach, 165–6
  characteristics of surface broach, 167
  method of measuring thickness of, 257–8
  pitch angle of, 116, 118
  spur gear, design example, 260–1
  virtual number of, 255
Teflon, 528
Temperature—
  cutting, 69–71
  effect on grinding machines, 287
  effect on measurement, 367
  lubricants dependence on high, 521

Temperature—*contd.*
  spark erosion, 292
Temperature-sensitive paints, 70
Tensile stress, 331
  in drawing, 317
Test piece—
  cemented carbide, 85
  machine tool, 44
Testing, of grinding wheels, 189
Texture, surface—
  geometry and, 475–6
  functional aspects of, 469–75
  measurement of, 413 *ff.*
  preparation of by machine, 475–85
  specification of, 461–2
  topographic assessment of, 418–49
Theory of friction, 514
Theory of lubrication, 515–22
Thermo-electric method of measuring cutting temperatures, 70
Thick-film lubrication, 515
Thickness—
  changes of in re-drawing, 327–31
  effect of drawing on, 316–17
  effect on by free drawing, 317–18, 319
Thickness control, 317
Thinning, differential, 332
Thread cutting, 229–31
  comparison of external methods, 238
Thread form, examination of, 404
Thread grinding, 236–8
Thread rolling, 229, 231–6
Thread-forming tool, 303
Threads
  elements of screw, 408
  mating, 408–9
  production of screw, 229–45
Three-point support, straightedge, 369
Through rolling, screw thread, 235–6
Through-feed grinding, 210
Thrust bearing, tilting-pad, 518–19
Tip circle, of gears, 251
Tilting-pad thrust bearing, 518–19
Titanium carbide, 85
Titanium oxide, in abrasives, 187
Tolansky, Professor, 446, 448
Tolerances, 186, 378–83, 384, 385, 386, 399, 406
  check gauge, 365–7
  gauge, 391–3
  in grinding, 195
  ring-gauge, 365
Tomlinson, Dr. G. A., 367, 442
Tomlinson skid instrument, 431
Tool bluntness, 83
Tool designers, 578
Tool edge, track of in turning operations, 96
Tool electrodes, 290, 292, 293, 298, 303 *ff.* 312, 313
Tool, forming, for screw cutting, 232
Tool grinding, 579–80
  anodic, 314–15
Tool holders, vibrating, 296
Tool life—
  criterion of, 86
  cutting speed and, 86–7
  economical, 90
  on lathe work, 94
Tool marks, 416
Tool material, effect of lubrication on, 83–4
Tool rest—
  alignment of, 48
  swivelled, 100, 101
Tool room, 578, 587 *ff.*
Tool-room slotting machine, 181–3
Tool stores, 578–9
Tool wear—
  chemical effects in, 86–7
  effect of angle clearance on, 88–9
  effect of rake angle on, 88–9
  effects of depth of cut, 87–8
Tools—
  accessibility of press, 346
  broken, extraction of, 290–1
  cutting diameter of rotating, 1, 3
  diamond, 476–8
  effect of on surface roughness, 77
  grinding carbide tools by anodic machining, 313
  lubrication of machine, 528–33
  milling, 116–30
  press, 352–7
  servo-systems for rotating, 296
  shaping and planing machine, 180
  single-point cutting, 229, 230–1
  slotting machine, 183
  spark machining, 292, 301–9
  typical for presswork, 353–7
  ultrasonic machine, 223–4
  wear in ultrasonic machining, 226
  wear on, 84–91
Tooling, considerations for presswork, 352–3
Tooling equipment for lathes, 111, 113
Tooling progressive, 356
Toolmaker's flat, 368
Toolmaker's microscopes, 376, 401
Toolmaker's straightedge, 368–9
Tooth, deep, of broach, 166
Tooth, gear, 253 *ff.*
Tooth depth, cutting, 273
Tooth flank, 251
"Topograph", 431
Topographic assessment of texture, 418–49
Topography of machined surfaces, 416
Toughening—
  data for, 313
  electric spark, 312–13
Torque, transmitted through gears, 266–7
Tracers, radioactive, 86
Training in the factory, 618–21
Transducers, 431, 437
  electromechanical, 217
Transfer-type drilling machines, 159–60
Transistors, 228
Transition fit, 381
Transmission characteristics of surface-texture instruments, 438–40
Transverse base pitch, 251
Transverse pitch, 251
Transverse pressure angle, 251
Travelling head shaper, 176–7
Traverse, speed of in grinding, 194–5
Traversing length, 453
Trip guards, 600, 606, 608
Triple-action press, 346
Try-squares, 369
Tungsten, use in furnaces, 573

Tungsten-carbide tool material, 85
"Tunnel" guard, 609
Turbine gears, 285
Turning—
    component forces in, 20
    cutting fluids for, 545
    diamond, 476-8
    operations in, 96–107
    process of, 92–6
Turning fixtures, 507–9
Turnover jig, 503–4
Turret lathes, 108–15
    tool life on, 94
Turret type drilling machines, 158–9
Twist drills, 144–9
Two-speed cutting cycle, in broaching, 167
Two-way clamping device, 494

Ultrasonic machining, 217–28
Undeformed chip thickness, 88, 90
Undercutting, 253, 255
Underwood, A., 442
Unified threads, 406
Unilateral hole system of fits, 383
Unilateral tolerancing, 380
Unit drilling machine, 156
Universal dividing head, 142, 143
Universal grinding machines, 213–14
Universal measuring block, 405
Universal milling machines, 132

Vee-die for stampings, 351
Vee-slide, 30
Velocity—
    cutting, 1 *et seq.*
    relative, 1
Velocity diagram of slotted link motions, 175–6
Velocity of cutting movement in turning, 20
Vernier callipers, 369–70
Vernier height gauge, 370
Vernier protractors, 371
Vertical boring machines, 107–8
Vertical broaches, 165
Vertical broaching machines, 169, 170
Vertical comparators, 373–4
Vertical milling machines, 132
Vertical projectors, 376
Very high temperature furnaces, 571–3
Vibration—
    effect on machined surface, 416
    in ultrasonic machining, 217, 222, 223
    of cutting tools, 71–5
    tool, 116
Virtual number of teeth, 255
Virtual pitch diameter, 255
Viscometers, 551
Viscosity, 515, 523, 530
    of lubricating oils, 550–1
Viscosity coefficient, 516
Viscosity curve, 552
Viscosity index, 552
    improvers, 524
Vitrefied grinding wheels, 188
Volatility, 523

Walking beam furnaces, 569
Ward Leonard control system, 174, 179
Ward-Leonard drive, 21
Water as dielectric, 293
Water-base fluids, 538
Water-resistant greases, 525
Waviness, texture, 416
Wavelength cut-off, 438–40
Waxes, chlorinated, 521
Wear, on cutting tools, 59, 84–91
    effects of depth of cut, 87–8
    in spark erosion, 301, 303
    in ultrasonic machining, 226
    lubricants and, 514
Wedge tool, simple, 51–3
Wedging force, 400
Weights and Measures Act, 1878, 361
Weingraber, Dr. H. von, 450
Wheel, crown, 270
Whitworth, Sir Joseph, 591
Whitworth quick-return motion, 176
Whitworth screw threads, 405
Wick feed oilers, 547
Wickman type gauges, 396
Work speed, grinding, 193
Work study, 585–6
Workhead, live spindle, 198, 199, 205
Workpiece materials, for lathes, 110–11
Works Council, 617
Works discipline, 621–2
Works manager, 575
Works rules, 617
Workshop—
    human relations in, 613–25
    surface assessment in the, 466, 468–75
Worm gears, 271–2
    cutting, 275–6
    design example, 265–6
    grinding, 286–7
    hobbing, 280
    shaving, 283–4
    super-finishing, 288
Worm-grinder, 286–7
Wringing of slip-gauges, 364

Yard, Imperial standard, 361, 362